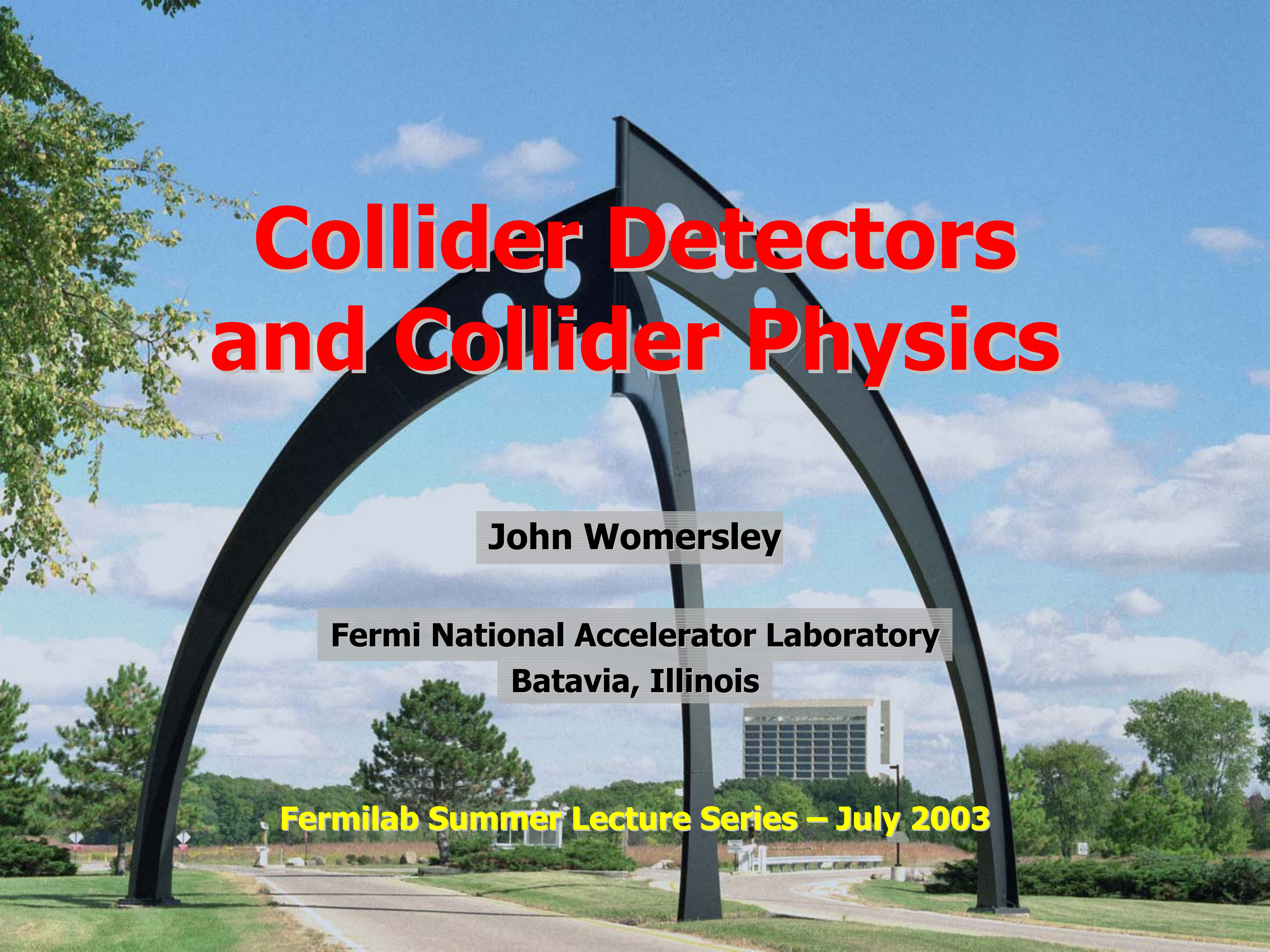


Collider Detectors and Collider Physics

John Womersley

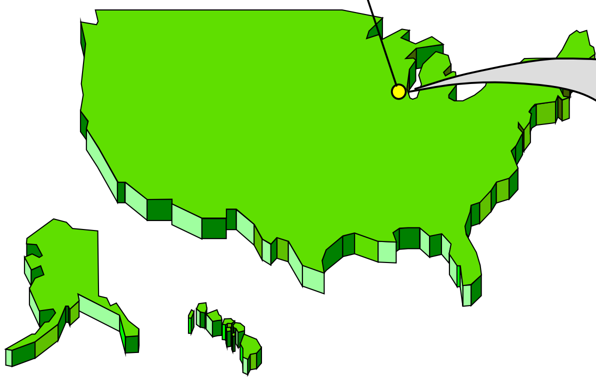
Fermi National Accelerator Laboratory
Batavia, Illinois

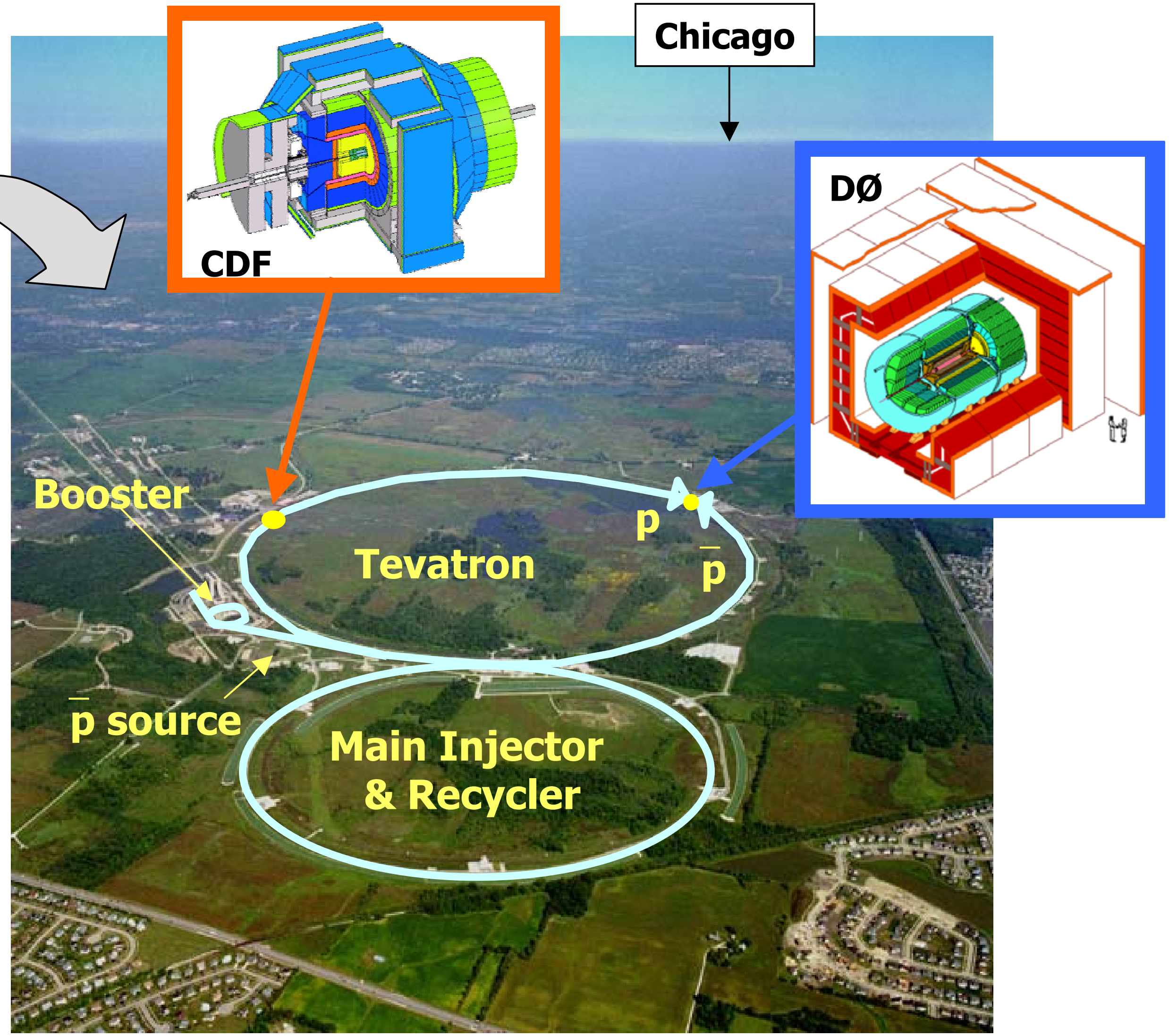
Fermilab Summer Lecture Series – July 2003

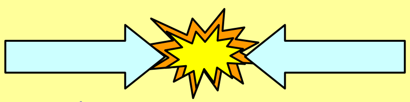
Outline

- What is the "Tevatron Collider" anyway?
- Why do we need one?
- What kind of questions are we attempting to answer with it?
- How do we do this?

Fermilab





p  $\bar{p}$

$\sqrt{s}$ =1.96 TeV

Δt = 396 ns

Run I 1992-95

Run II 2001-09(?)

100 × larger dataset at increased energy

What is the universe made of?

- It is often claimed that humans are naturally curious
  - Maybe so, but in my experience they often try to answer this kind of question by sitting and talking and coming up with explanations
    - Call it philosophy, or call it shooting the breeze
- The only <u>reliable</u> way to answer this question is by directly enquiring through experiment
  - not necessarily a "natural human activity", but perhaps the greatest human invention
  - Something that is not understood, and therefore not particularly liked, by many people
  - often tolerated mainly because it is useful
- Something to think about, especially when we are trying to explain scientific projects that do not, a priori, seem useful

Experiment has taught us:

- Complex structures in the universe are made by combining simple objects in different ways
  - Periodic Table

- Apparently diverse phenomena are often different manifestations of the same underlying physics
  - Orbits of planets and apples falling from trees

- Almost everything is made of small objects that like to stick together
  - Particles and Forces

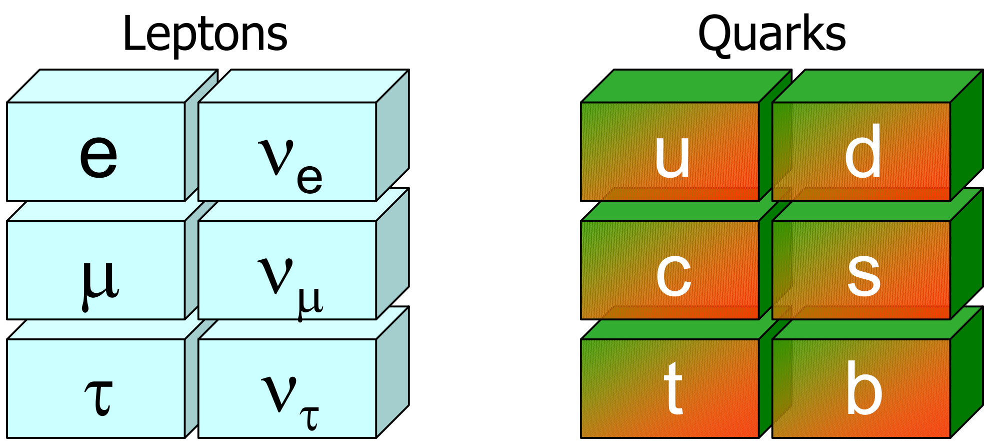
- Everyday intuition is not necessarily a good guide
  - We live in a quantum world, even if it's not obvious to us

Particles and Forces Timeline

- **1897-1920's**
  - The electron (vacuum tubes)
  - Atomic physics, X-rays, quantum mechanics
- **1930's**
  - The nucleus (Rutherford's experiment)
- **1940's**
  - Nuclear physics
- **1950's**
  - Particle physics (explosion of mesons and baryons)
  - Quantum Field Theory (Feynman et al.)
- **1960's – 1970's**
  - Quarks and leptons
- **1980's**
  - Electroweak Unification, W and Z bosons
- **1990's**
  - Consolidation of the Standard Model, top quark
  - Increasing interest in "Quarks to the Cosmos"

"Standard Model" of Particles and Forces

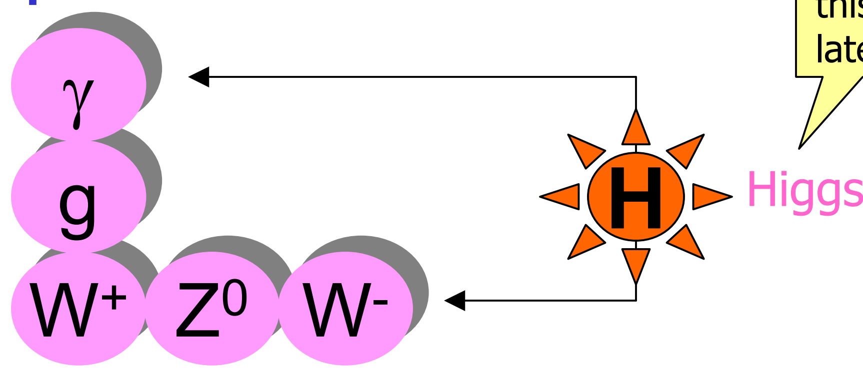
- **Point like, spin-½ fermionic constituents**



- **Which interact by exchanging spin-1 vector bosons**

Electromagnetic	10^{-2}
Strong	1
Weak	10^{-6}
Gravity	10^{-40}

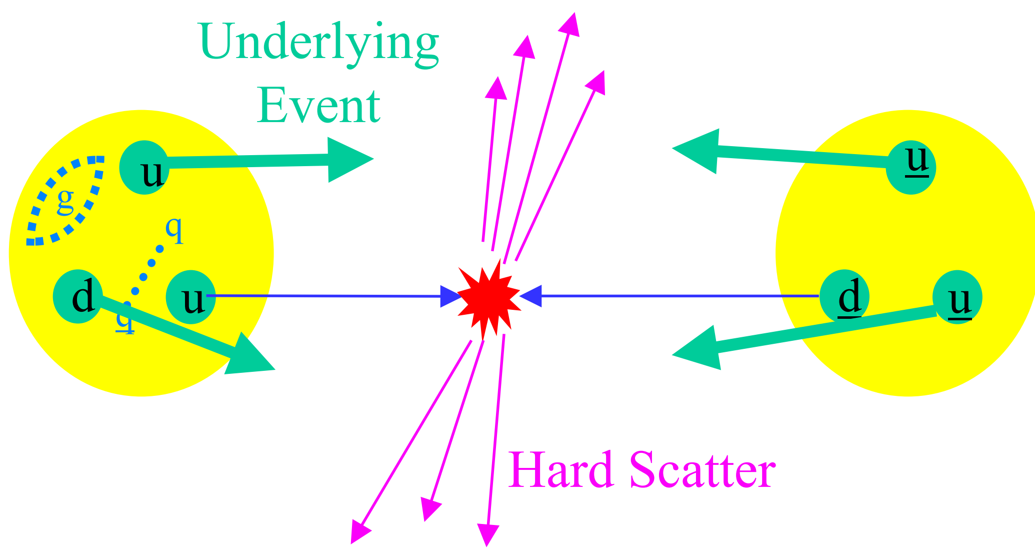
Relative strengths



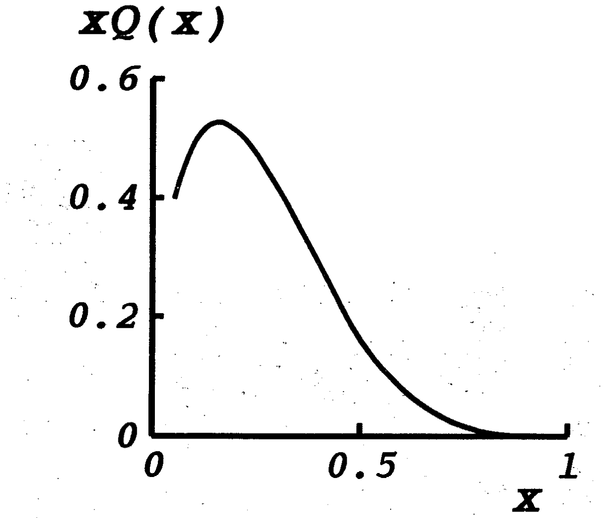
We'll come back to this guy later

Particle Accelerators

- Accelerators allow us to explore the interactions of particles at high energies
  - See the underlying physics not the dressing
- We can collide beams of either electrons or protons
  - Because electron beams radiate when accelerated, proton accelerators are the best way to reach very high energies (electron accelerators play an important complementary role)
- Proton-antiproton collision:

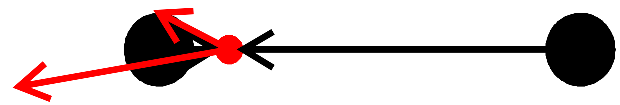


Proton-Antiproton Collisions



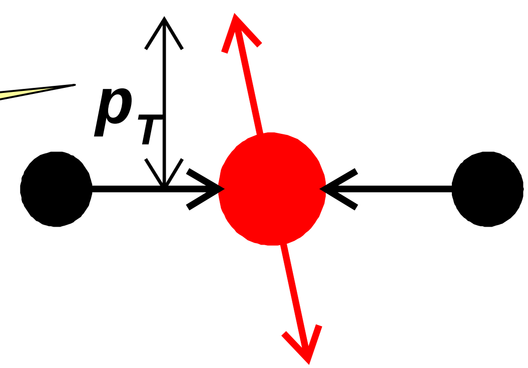
For every proton there is a probability for a single quark (or gluon) to carry a fraction "x" of the proton momentum

Small x = small energy, products boosted along beam direction

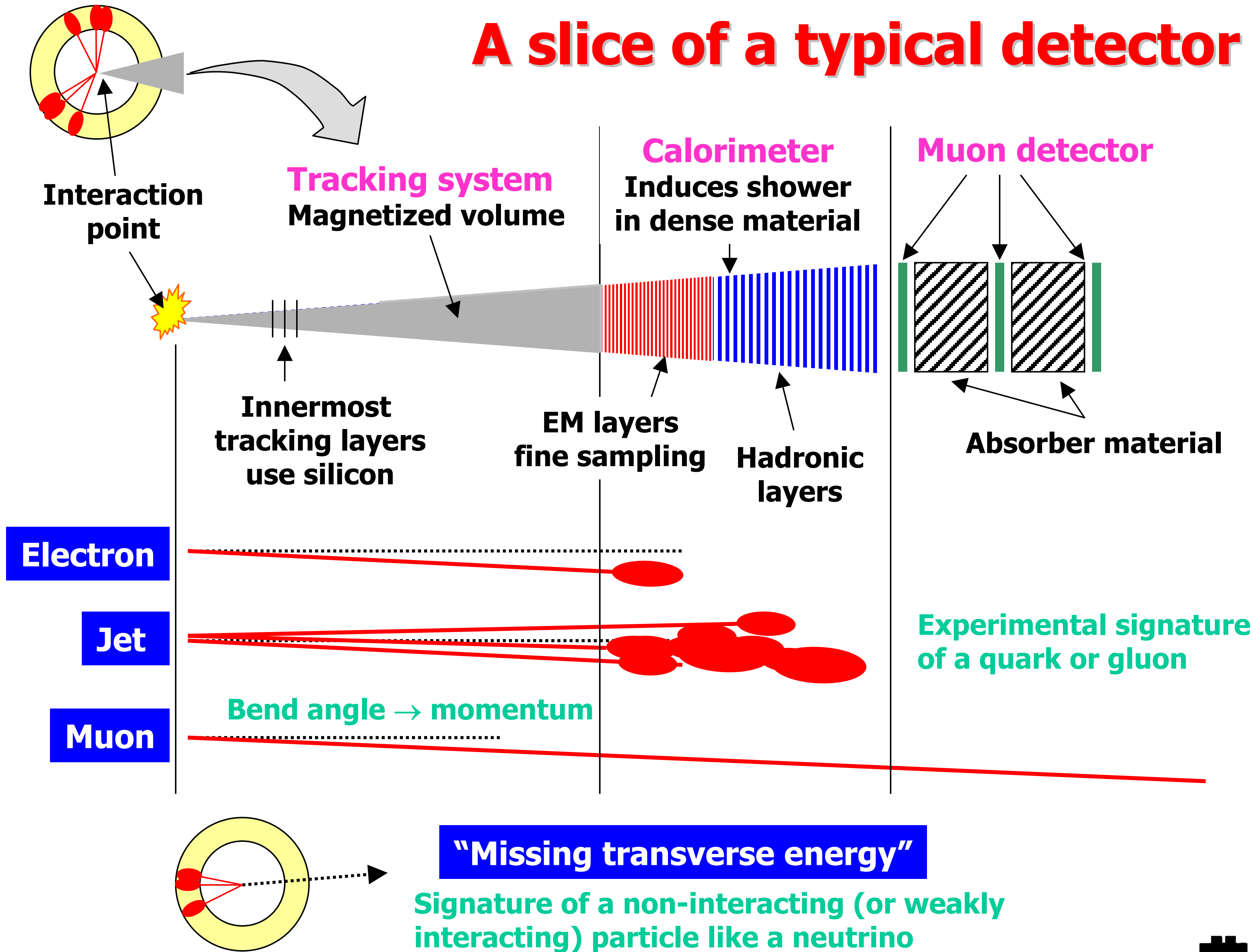


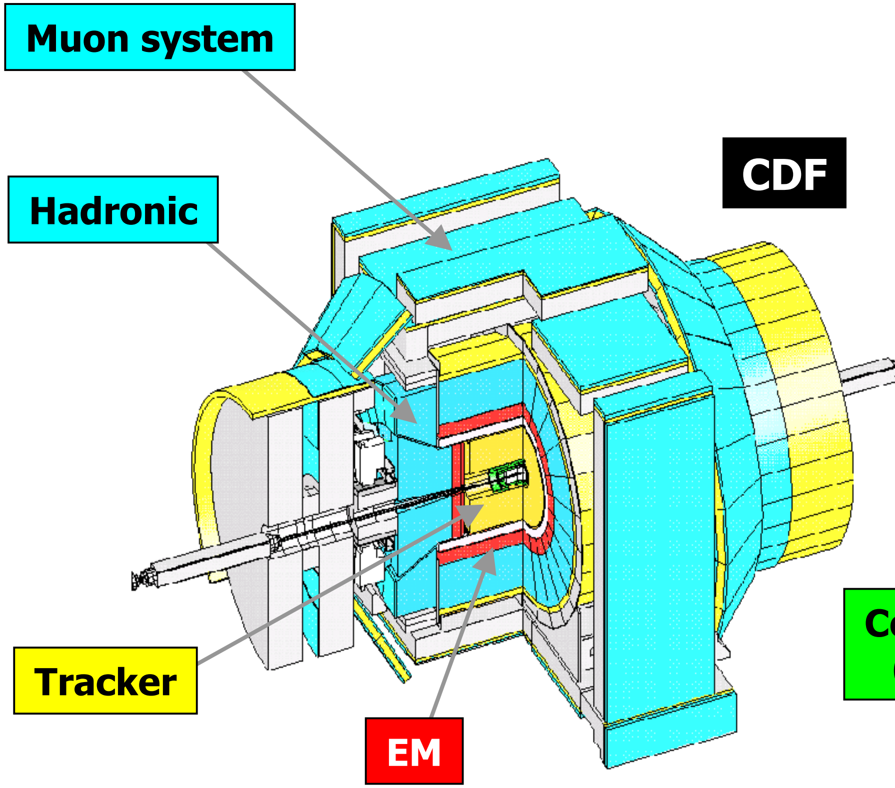
Large x = large energy, can create massive objects whose decay products have a large momentum transverse to the beam

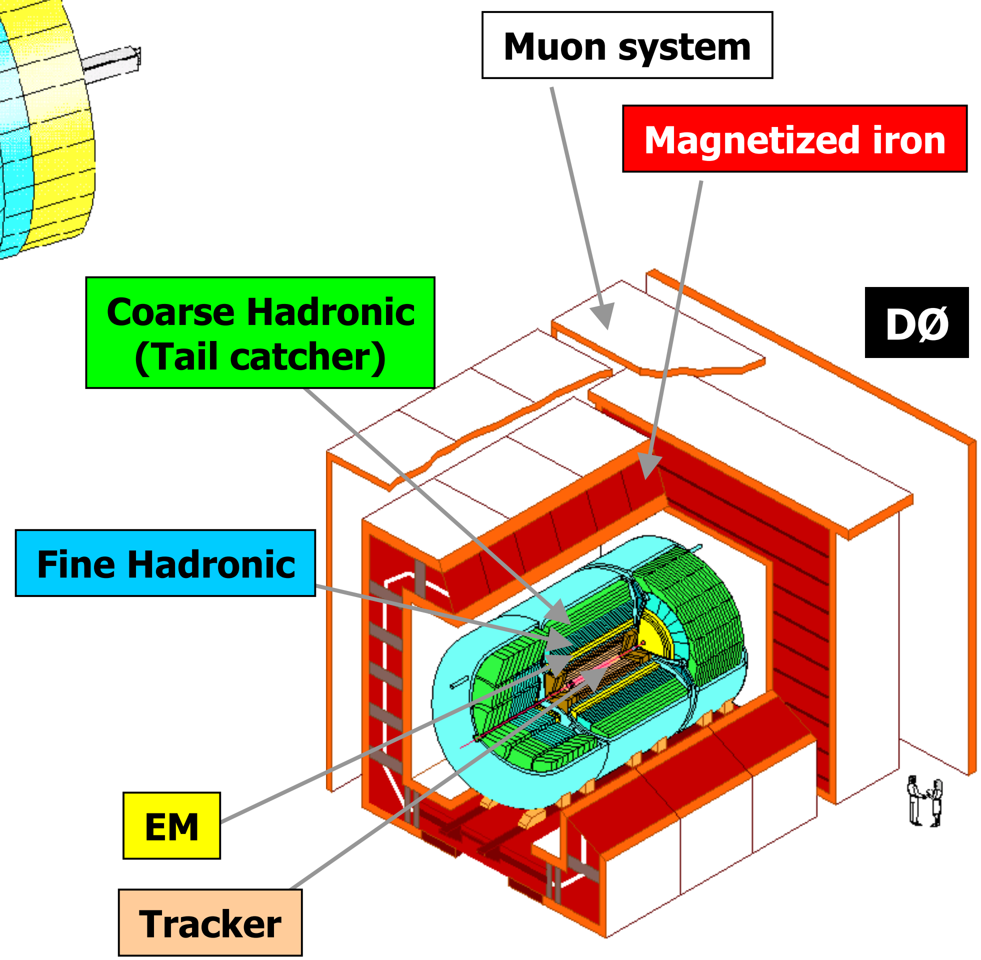
A good way to tell that a hard (and therefore interesting) collision occurred.
Forms the basis of on-line event selection ("triggering")

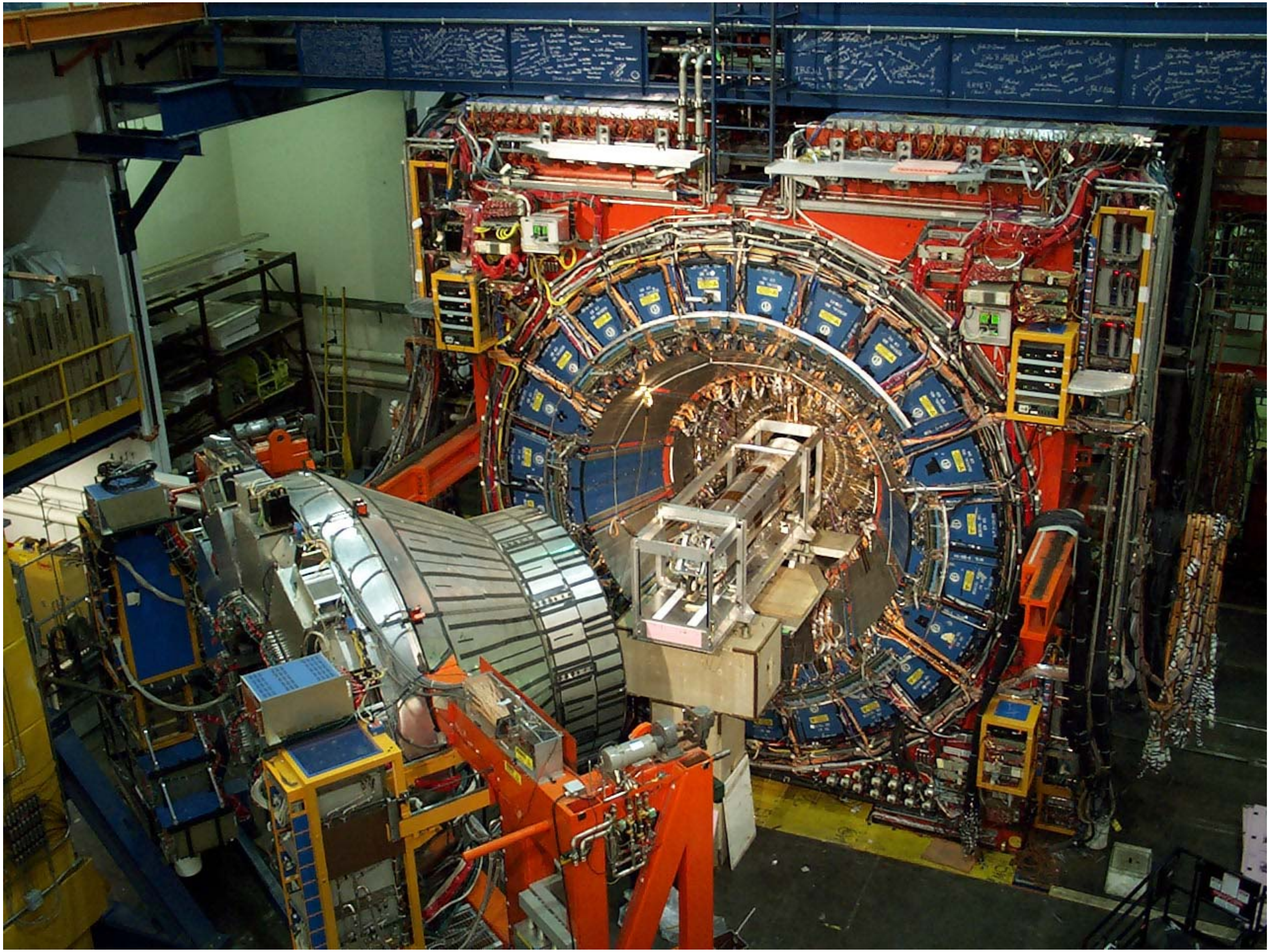


A slice of a typical detector




Muon system
Hadronic
CDF
Tracker
EM

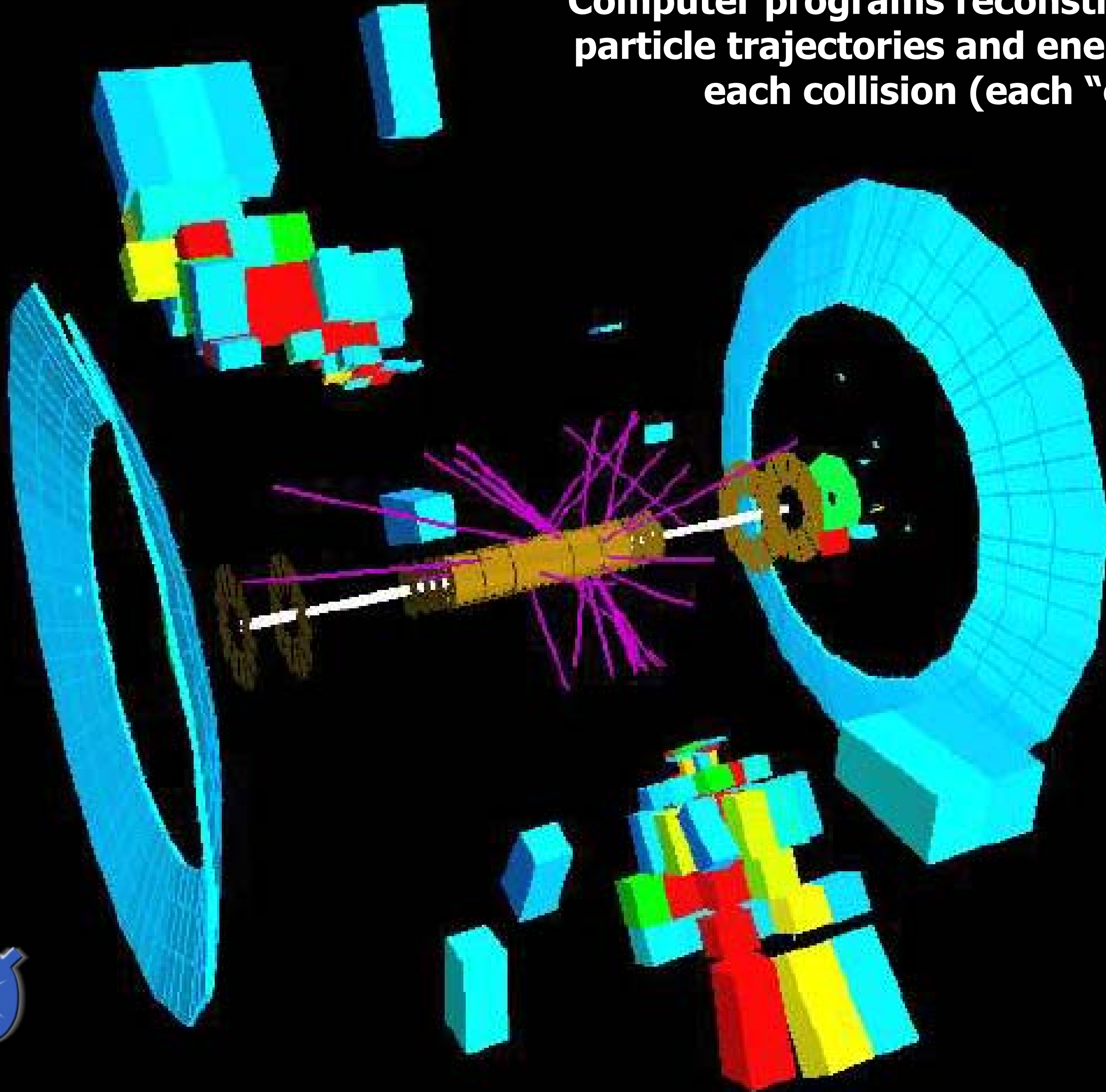

Muon system
Magnetized iron
Coarse Hadronic
(Tail catcher)
DØ
Fine Hadronic
EM
Tracker



Installing silicon tracker, prior to CDF detector roll-in

DØ detector installed in the Collision Hall, January 2001

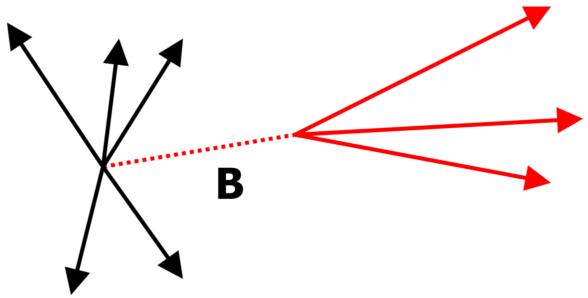
Computer programs reconstruct the particle trajectories and energies in each collision (each "event")



Displaced vertex tagging

- The ability to identify b-quarks is very important in collider physics
  - signatures for the top quark, supersymmetry, Higgs boson

- b quark forms a B-meson, travels ~ 1mm before decaying



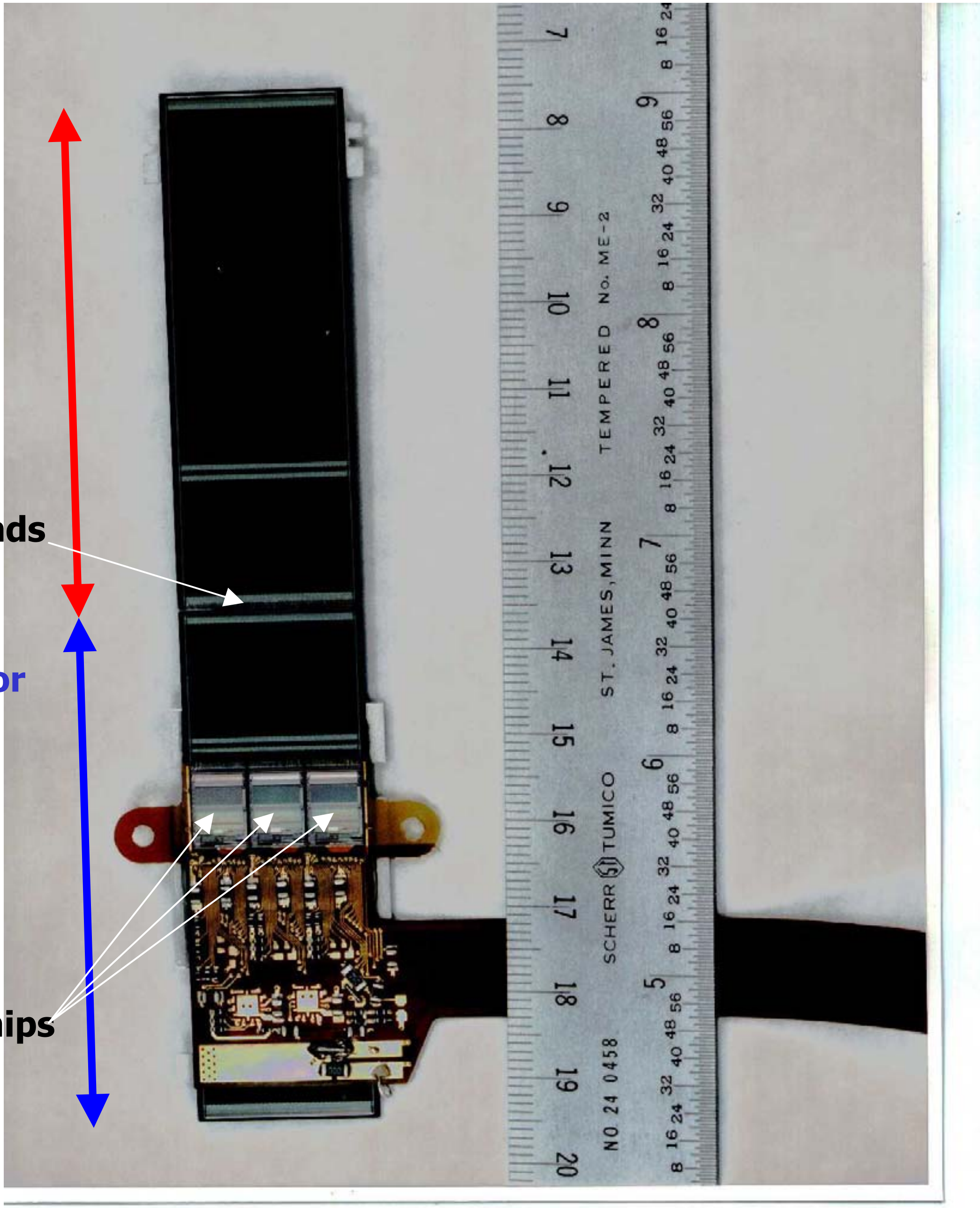
- to reconstruct this decay, need to measure tracks with a precision at the 10μm level

Silicon sensor

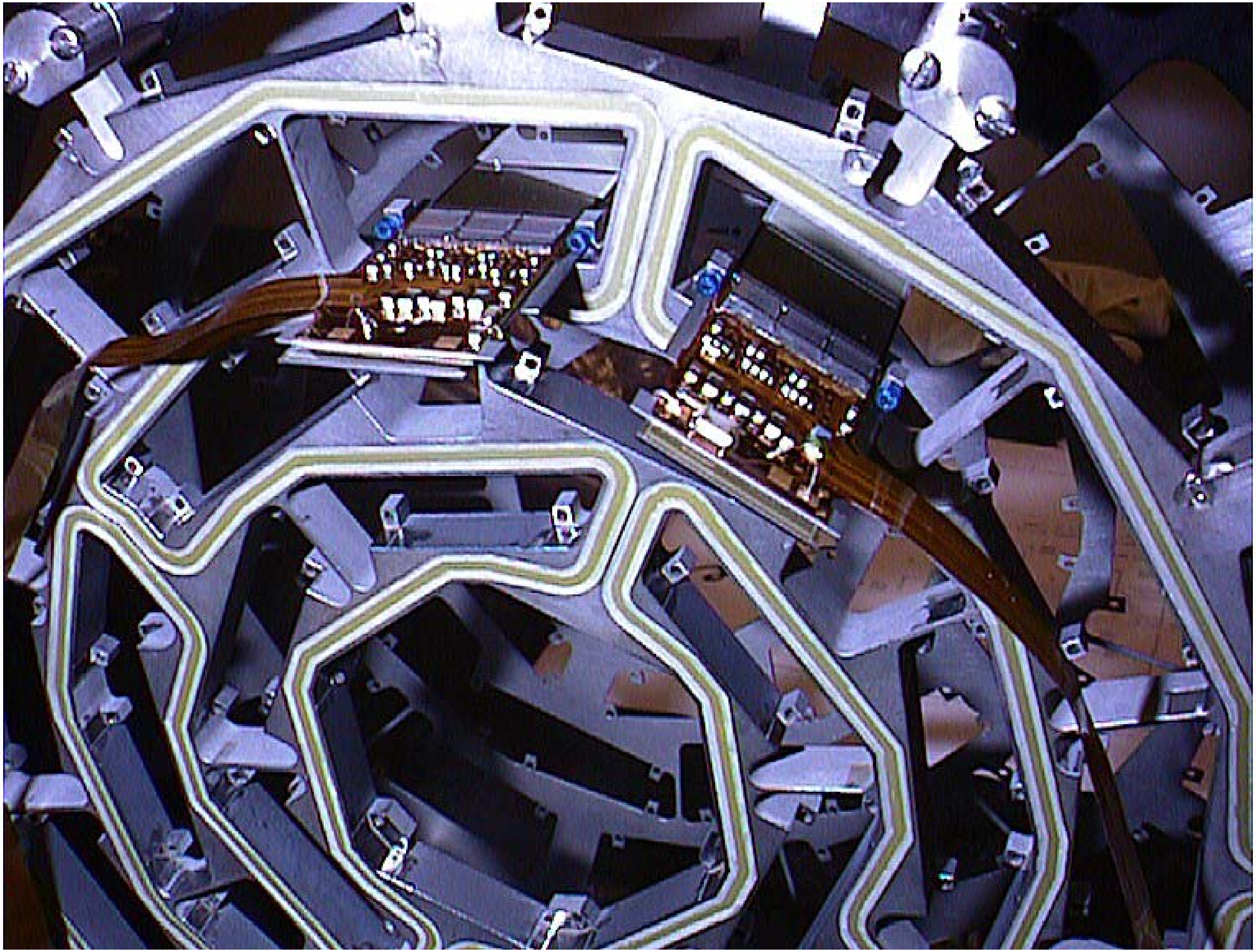
Wire bonds

Silicon sensor

SVX2e readout chips



HDI (flex circuit readout)

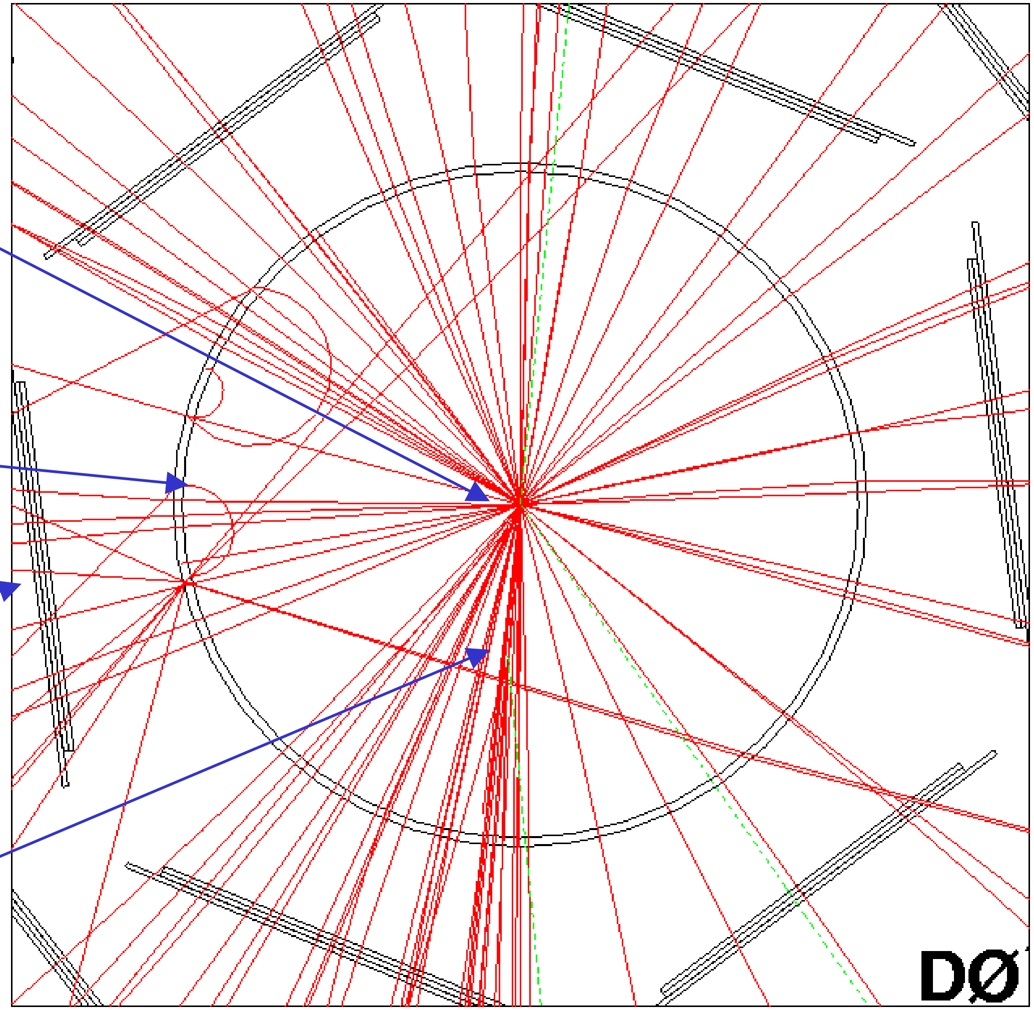


Interaction point ("primary vertex")

Beampipe

Silicon detector

B decay ("secondary vertex")

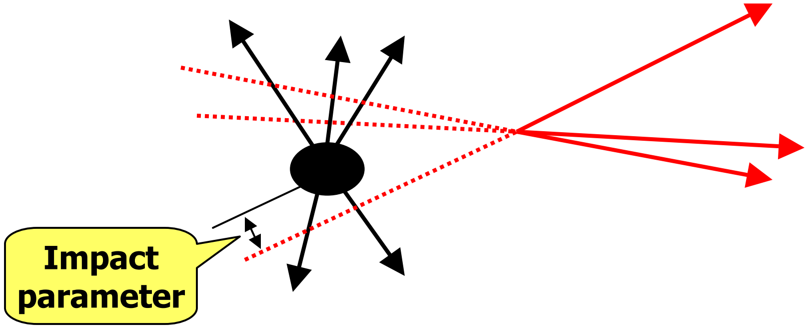


1 inch

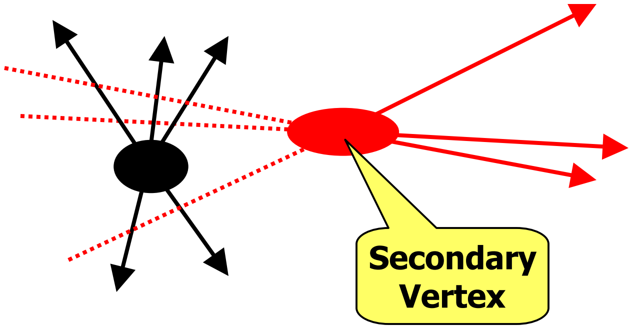
This green track clearly does not originate at the primary vertex

B-tagging

- Typical algorithms
  - require 2 or 3 tracks with significant impact parameter (distance of closest approach to the fitted primary vertex)

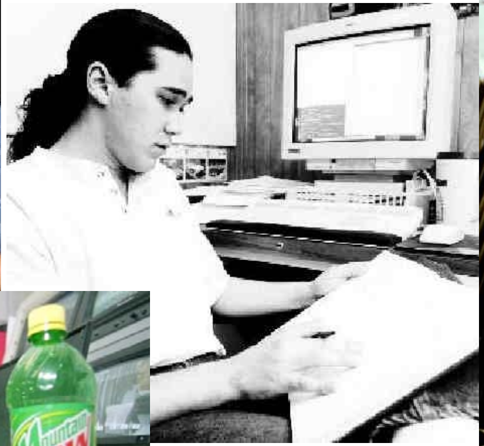


  - reconstruct a secondary vertex



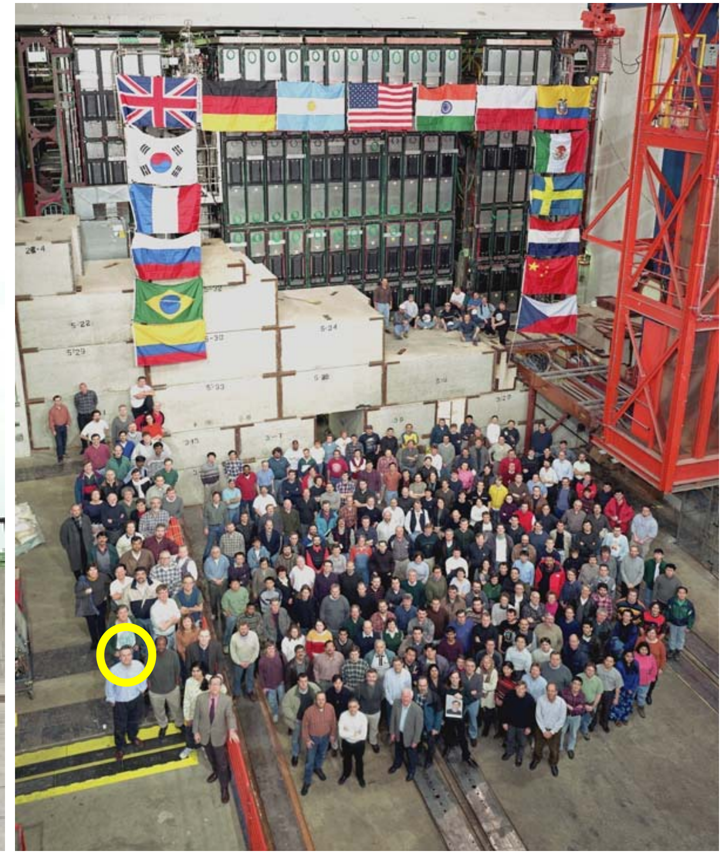
What do physicists actually do?

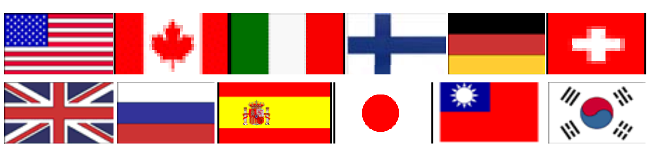
- **Design and build hardware**
  - **Detectors, electronics**
- **Write software**
- **Operate the detector**
- **Interpret data**
- **Present, refine, discuss our results among ourselves**
- **Publish papers**



Two Worldwide Collaborations

More than 50% non-US: a central part of the world HEP program





12 countries, 59 institutions

767 ~~706~~ physicists

19 ~~18~~ countries, 80 ~~78~~ institutions

670 ~~664~~ physicists

John Womersley

Remote International Monitoring for the DØ Experiment

Detector Monitoring data sent in real time over the internet

2 am

Fermilab

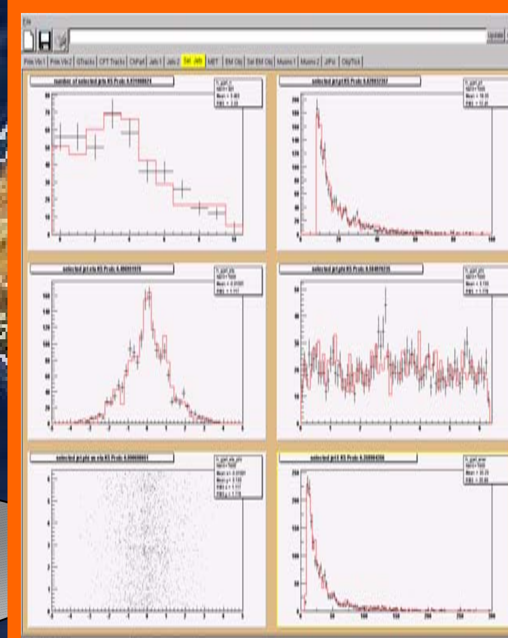
9 am

NIKHEF Amsterdam

DØ physicists in Europe use the internet and monitoring programs to examine collider data in real time and to evaluate detector performance and data quality.

They use web tools to report this information back to their colleagues at Fermilab.

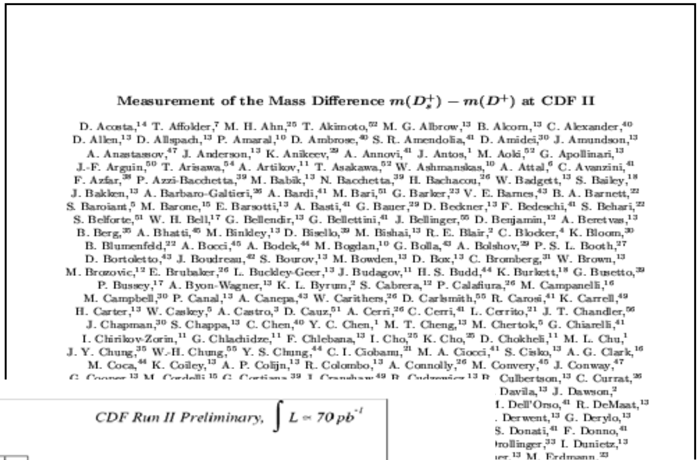
DØ detector



The online monitoring project has been developed by DØ physicists and is coordinated by Dr. Pushpa Bhat from Fermilab. Jason Webb, a DeVry University, Chicago, undergraduate student is helping develop and maintain the interactive tools for the remote physicists.

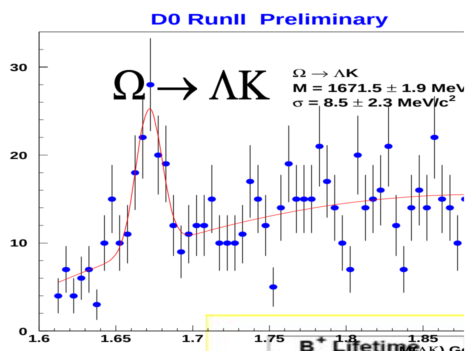
Current Operations Status

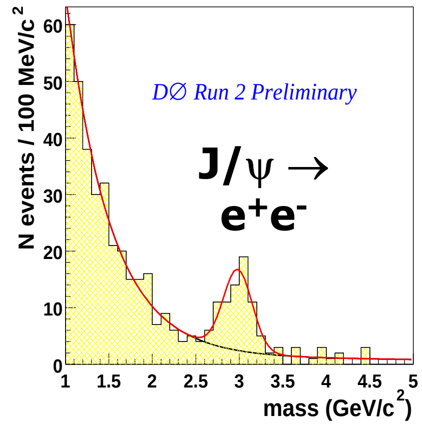
- Both experiments are operating well and recording physics quality data with high (~ 90%) efficiency
- 100-140 pb^{-1} being used for analysis for summer 2003
- Data are being reconstructed within a few days

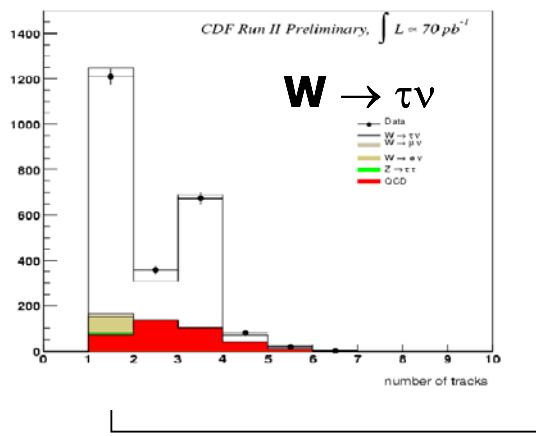


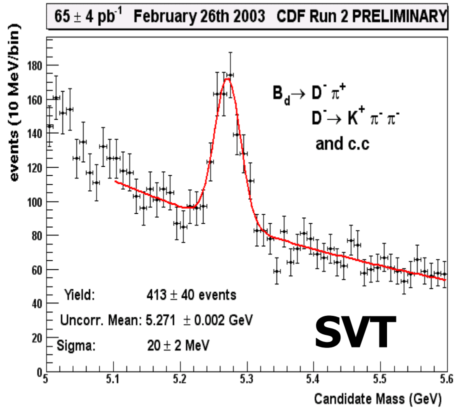
Measurement of the Mass Difference $m(D_s^+) - m(D^+)$ at CDF II

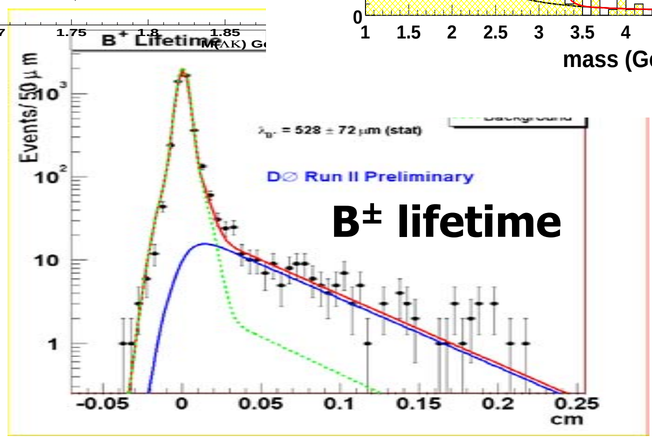
D. Acosta,[14] T. Affolder,[7] M. H. Ahn,[25] T. Akimoto,[52] M. G. Albrow,[13] B. Alcorn,[13] C. Alexander,[40] D. Allen,[13] D. Allspach,[13] P. Amaral,[10] D. Ambrose,[40] S. R. Amendolia,[41] D. Amidei,[30] J. Amundson,[13] A. Anastassov,[47] J. Anderson,[13] K. Anikeev,[29] A. Annovi,[41] J. Antos,[1] M. Aoki,[52] G. Apollinari,[13] J.-F. Arguin,[50] T. Arisawa,[54] A. Artikov,[11] T. Asakawa,[52] W. Ashmanskas,[10] A. Attal,[6] C. Avanzini,[41] F. Azfar,[38] P. Azzi-Bacchetta,[39] M. Babik,[13] N. Bacchetta,[39] H. Bachacou,[26] W. Badgett,[13] S. Bailey,[18] J. Bakken,[13] A. Barbaro-Galtieri,[26] A. Bardi,[41] M. Bari,[51] G. Barker,[23] V. E. Barnes,[43] B. A. Barnett,[22] S. Baroiant,[5] M. Barone,[15] E. Barsotti,[13] A. Basti,[41] G. Bauer,[29] D. Beckner,[13] F. Bedeschi,[41] S. Behari,[22] S. Belforte,[51] W. H. Bell,[17] G. Bellendir,[13] G. Bellettini,[41] J. Bellinger,[55] D. Benjamin,[12] A. Beretvas,[13] B. Berg,[35] A. Bhatti,[45] M. Binkley,[13] D. Bisello,[39] M. Bishai,[13] R. E. Blair,[2] C. Blocker,[4] K. Bloom,[30] B. Blumenfeld,[22] A. Bocci,[45] A. Bodek,[44] M. Bogdan,[10] G. Bolla,[43] A. Bolshov,[29] P. S. L. Booth,[27] D. Bortoletto,[43] J. Boudreau,[42] S. Bourov,[13] M. Bowden,[13] D. Box,[13] C. Bromberg,[31] W. Brown,[13] M. Brozovic,[12] E. Brubaker,[26] L. Buckley-Geer,[13] J. Budagov,[11] H. S. Budd,[44] K. Burkett,[18] G. Busetto,[39] P. Bussey,[17] A. Byon-Wagner,[13] K. L. Byrum,[2] S. Cabrera,[12] P. Calafiura,[26] M. Campanelli,[16] M. Campbell,[30] P. Canal,[13] A. Canepa,[43] W. Carithers,[26] D. Carlsmith,[55] R. Carosi,[41] K. Carrell,[49] H. Carter,[13] W. Caskey,[5] A. Castro,[3] D. Cauz,[51] A. Cerri,[26] C. Cerri,[41] L. Cerrito,[21] J. T. Chandler,[56] J. Chapman,[30] S. Chappa,[13] C. Chen,[40] Y. C. Chen,[1] M. T. Cheng,[13] M. Chertok,[5] G. Chiarelli,[41] I. Chirikov-Zorin,[11] G. Chlachidze,[11] F. Chlebana,[13] I. Cho,[25] K. Cho,[25] D. Chokheli,[11] M. L. Chu,[1] J. Y. Chung,[35] W.-H. Chung,[55] Y. S. Chung,[44] C. I. Ciobanu,[21] M. A. Ciocci,[41] S. Cisko,[13] A. G. Clark,[16] M. Coca,[44] K. Coiley,[13] A. P. Colijn,[13] R. Colombo,[13] A. Connolly,[26] M. Convery,[45] J. Conway,[47]











What next?

- You've got this great standard model and you know all about all of the particles and forces involved. So why do you need to do these experiments? Isn't it all done?

- Yes, we know a lot, but we know a lot less than we would like, and we know enough now to ask some deeper questions
  - the paradox of the "circumference of knowledge"

Deeper Questions

Not just "what happens?" type of questions — "why does it happen?"

For example

- Why are some forces weak and others strong?
- What is the dark matter that seems to be responsible for cosmic structure?
- What is the structure of spacetime?

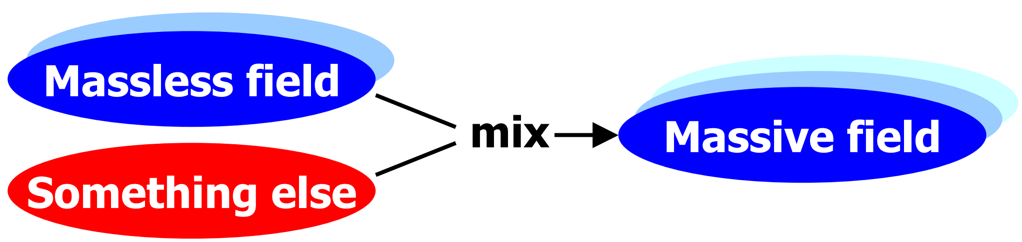
Not purely particle physics questions any more
Particle physics is the DNA of the universe

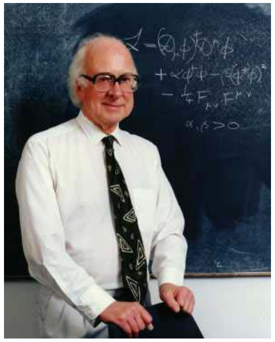
Q:

- **Why are some forces weak and others strong?**
  - **Is the Universe filled with an energy field?**
  - **Is there a unification of forces at very high energies?** *(We'll come back to this later in the talk)*

Electroweak Symmetry Breaking

- Photons and W/Z bosons couple to particles with the same strength
  - Electroweak unification
- Yet while the universe (and this room) is filled with photons, W's and Z's mediate a weak force that occurs inside nuclei in radioactive beta decay
  - This is because the W and Z are massive particles
  - The unification is "broken"
- Where does this mass (the symmetry breaking) come from?
  - Not like the mass of the proton, which is the binding energy of its constituents
- In the Standard Model, the W and Z get their mass because the universe is filled with an energy field, called the Higgs field, with which they interact (and in fact mix)
  - The universe is a refractive medium for W's and Z's





The "Higgs Mechanism"

The Higgs Mechanism

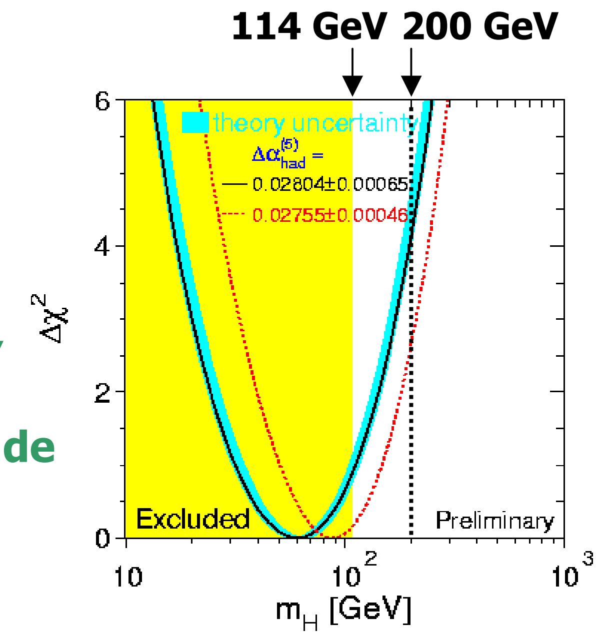
- **In the Standard Model (Glashow, Weinberg, Salam, ‘t Hooft, Veltmann)**
  - “electroweak symmetry breaking” occurs through a scalar field which permeates all of space with a finite vacuum expectation value
    - Cosmological implications: a source of “Dark Energy”
    - but 10^{54} times too much energy density!
  - If the same field couples to fermions $\rightarrow$ generates fermion masses

- **An appealing picture: is it correct?**
  - One clear and testable prediction: there exists a **neutral scalar particle** which is an excitation of the Higgs field

We want to excite this field in the lab and study its quanta!
“Pluck the violin-string of the universe”

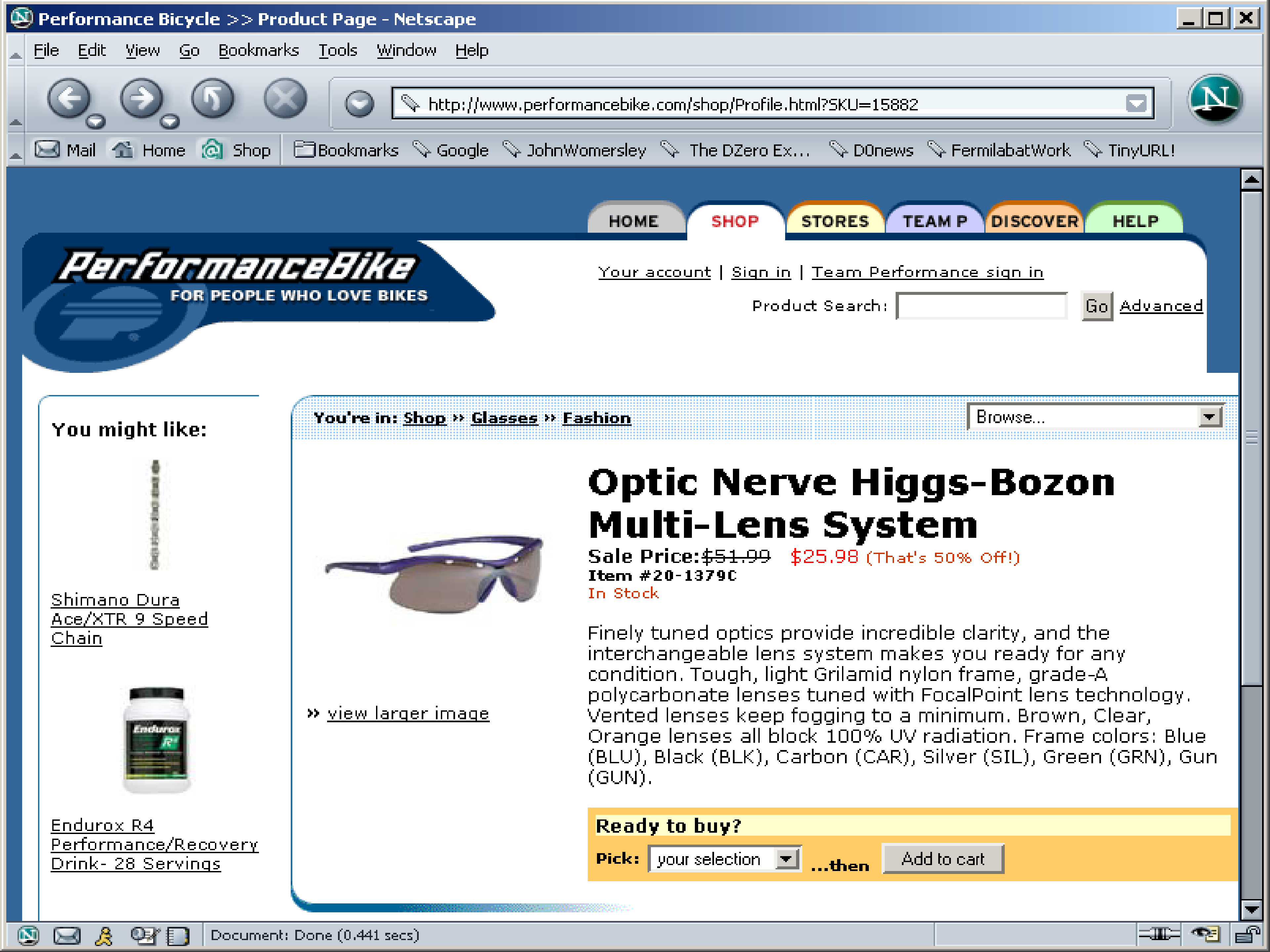
  - All its properties (production and decay rates, couplings) are fixed within the SM, except for its own mass

Searching for the Higgs



- **In the last decade, the focus was on experiments at the LEP e^+e^- collider at CERN (European Laboratory for Particle Physics)**
  - **precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of $m_H \sim 200$ GeV**
  - **direct searches for Higgs production exclude $m_H < 114$ GeV**
- **Summer and Autumn 2000: Hints of a Higgs**
  - **the LEP data may be giving some indication of a Higgs with mass 115 GeV (right at the limit of sensitivity)**
  - **despite these hints, CERN management decided to shut off LEP operations in order to start construction on the Large Hadron Collider (a new accelerator with seven times the energy of the Tevatron)**
- **Until the end of the decade, Fermilab has a unique opportunity to discover or exclude this object – then pass the baton to the LHC**


University of Durham
THE HIGGS BOSON
1964
Peter Higgs suggested introducing
widely accepted scenario.
The Higgs boson is the only missing ingredient of the Standard Model
2008
Ogden Centre for Fundamental Physics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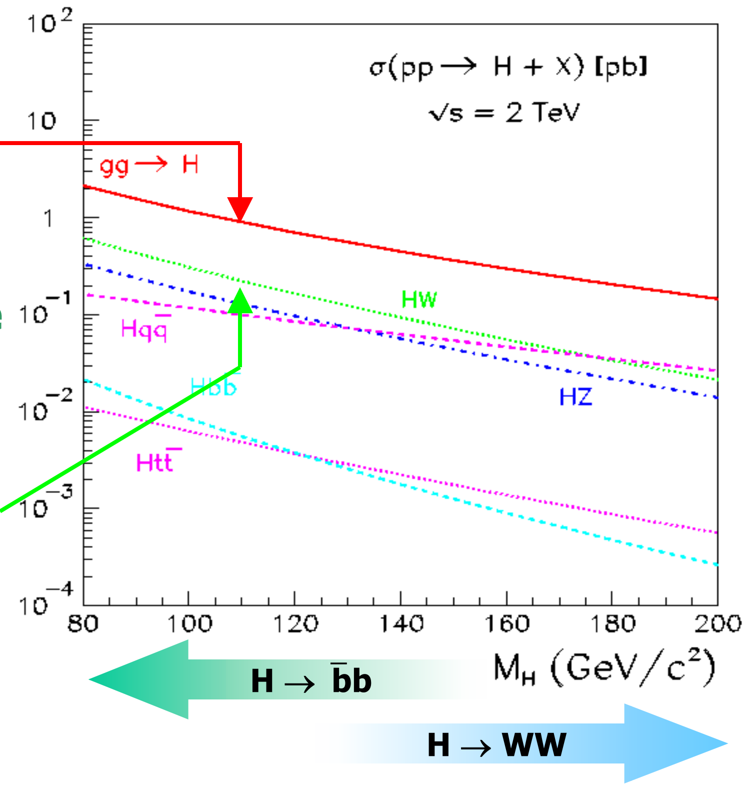
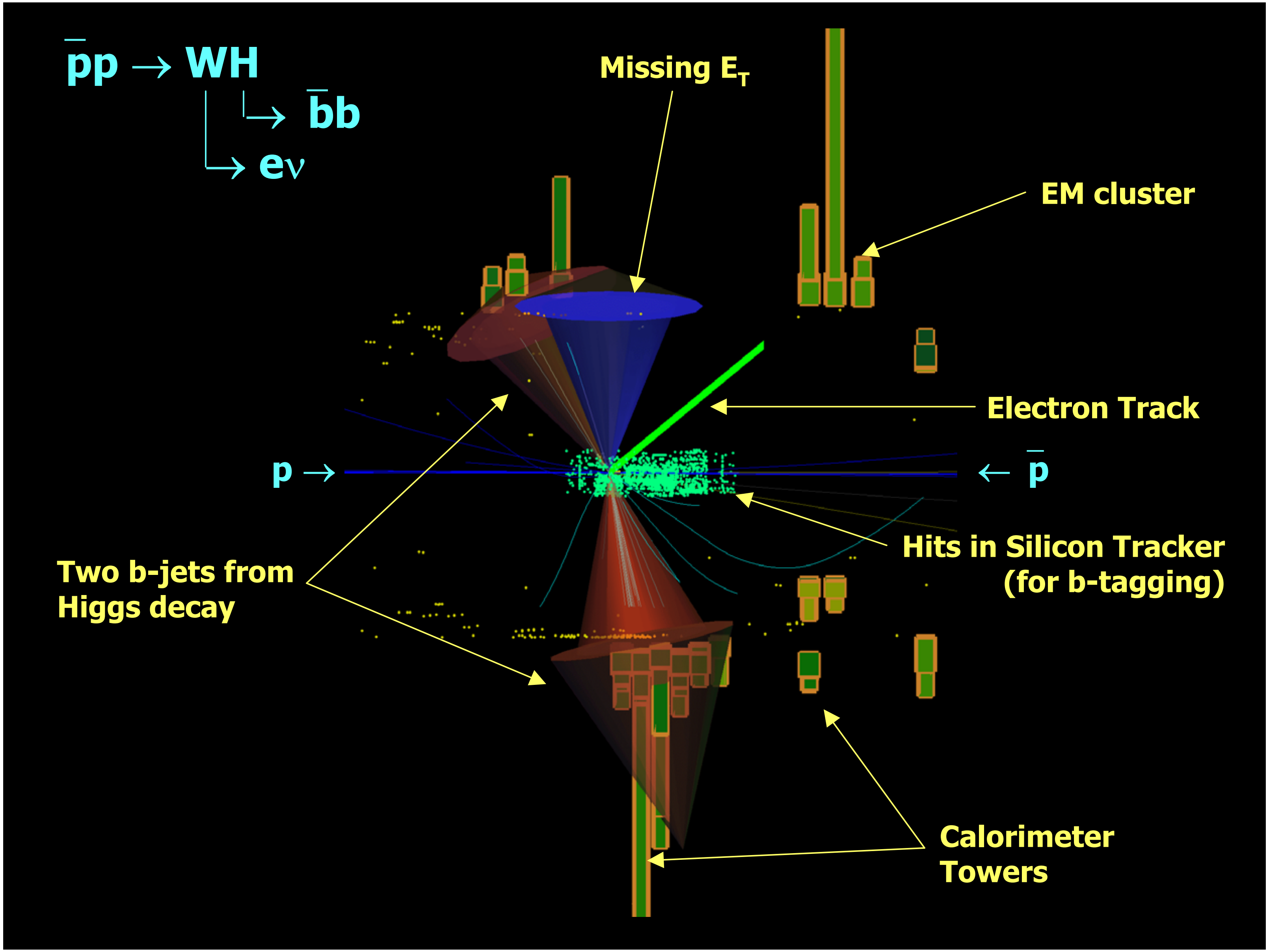
Pick: your selection ...then Add to cart
Document: Done (0.441 secs)

Higgs Hunting at the Tevatron

- For any given Higgs mass, the production cross section and decays are all calculable within the Standard Model
- Inclusive Higgs cross section is quite high: ~ 1pb
  - for masses below ~ 140 GeV, the dominant decay is $H \to bb$ which is swamped by background
  - at higher masses, can use inclusive production plus WW decays
- The best bet below ~ 140 GeV appears to be associated production of H plus a W or Z
  - leptonic decays of W/Z help give the needed background rejection
  - cross section ~ 0.2 pb



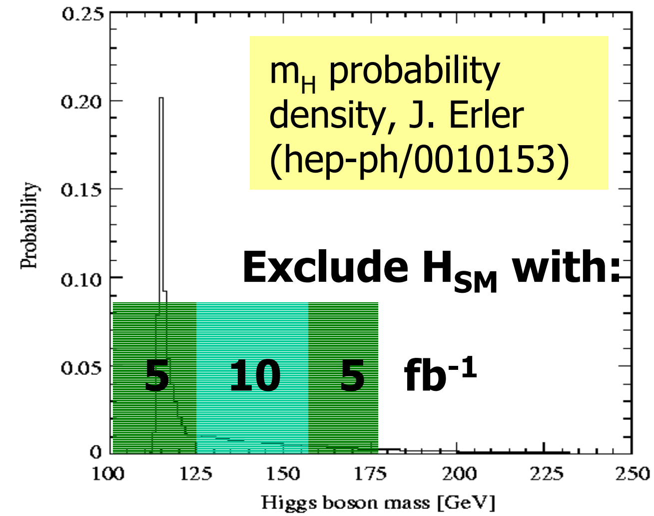
Dominant decay mode


$\bar{p}p \rightarrow WH$
$\hookrightarrow \bar{b}b$
$\hookrightarrow e\nu$
Missing E_T
EM cluster
Electron Track
$p \rightarrow$
$\leftarrow \bar{p}$
Hits in Silicon Tracker
(for b-tagging)
Two b-jets from
Higgs decay
Calorimeter
Towers

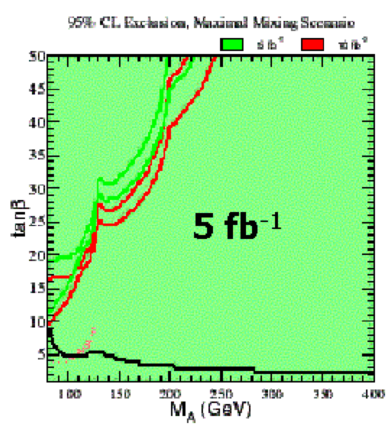
What if we see nothing?

As long as we have adequate sensitivity, exclusion of a Higgs would itself be a very important discovery for the Tevatron

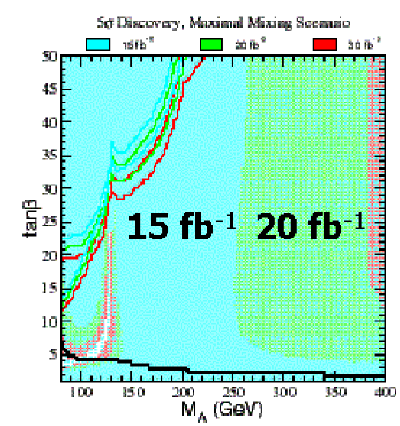
- In the SM, can exclude most of the allowed mass range
- If supersymmetry (SUSY) is correct, we can potentially exclude <u>all</u> the remaining parameter space
- Would certainly make life "interesting" for the theorists



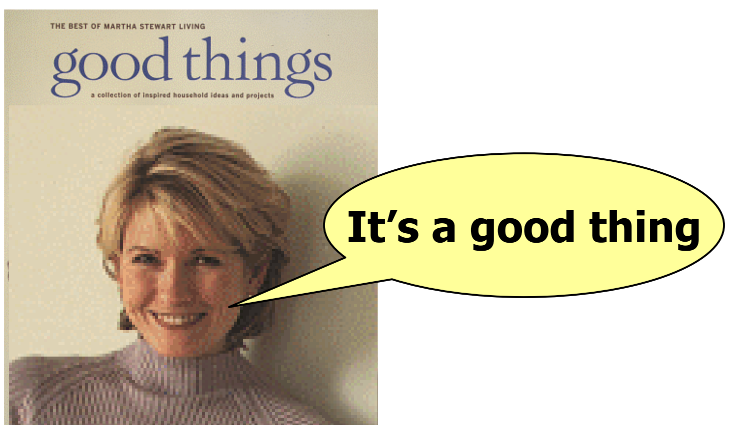
95% exclusion



5σ discovery

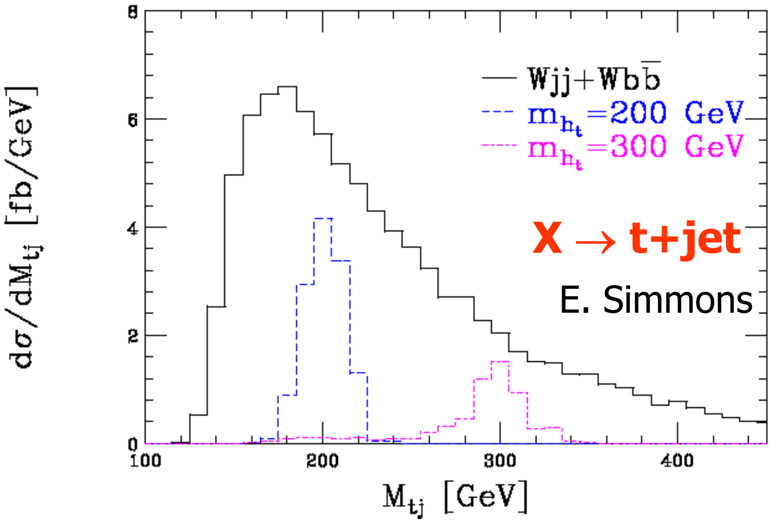


Exclusion and discovery for SUSY Higgs sector, maximal stop mixing, sparticle masses = 1 TeV

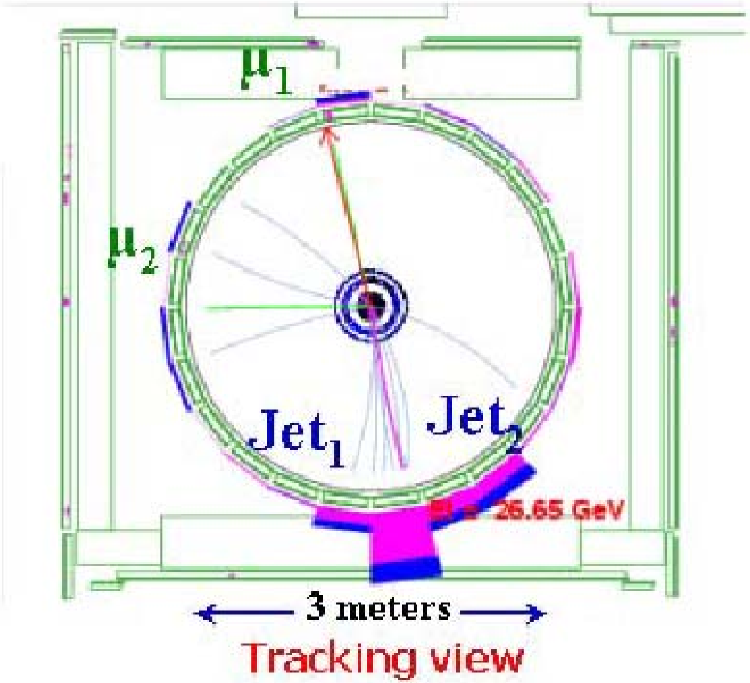


The Top Quark

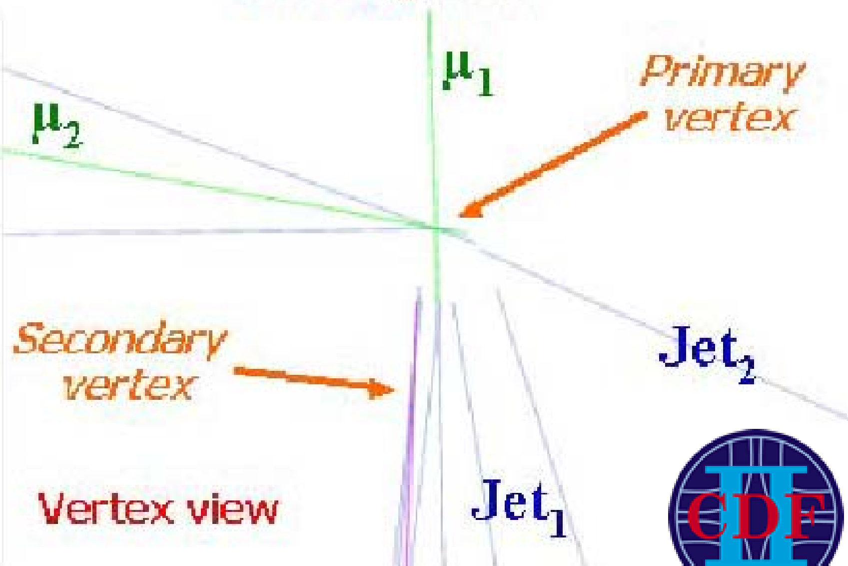
- Why, alone among the elementary fermions, does the top quark couple strongly to the Higgs field?
  - Is nature giving us a hint here?
    - Is the mechanism of fermion mass generation indeed the same as that of EW symmetry breaking?
  - The top is a window to the origin of fermion masses
- The Tevatron Collider is the world's only source of top quarks
- We are measuring its
  - Mass
  - Production cross section
  - Spin
    - Through top-antitop spin correlations
  - Electroweak properties
    - Through single top production
- Any surprises, anomalies?



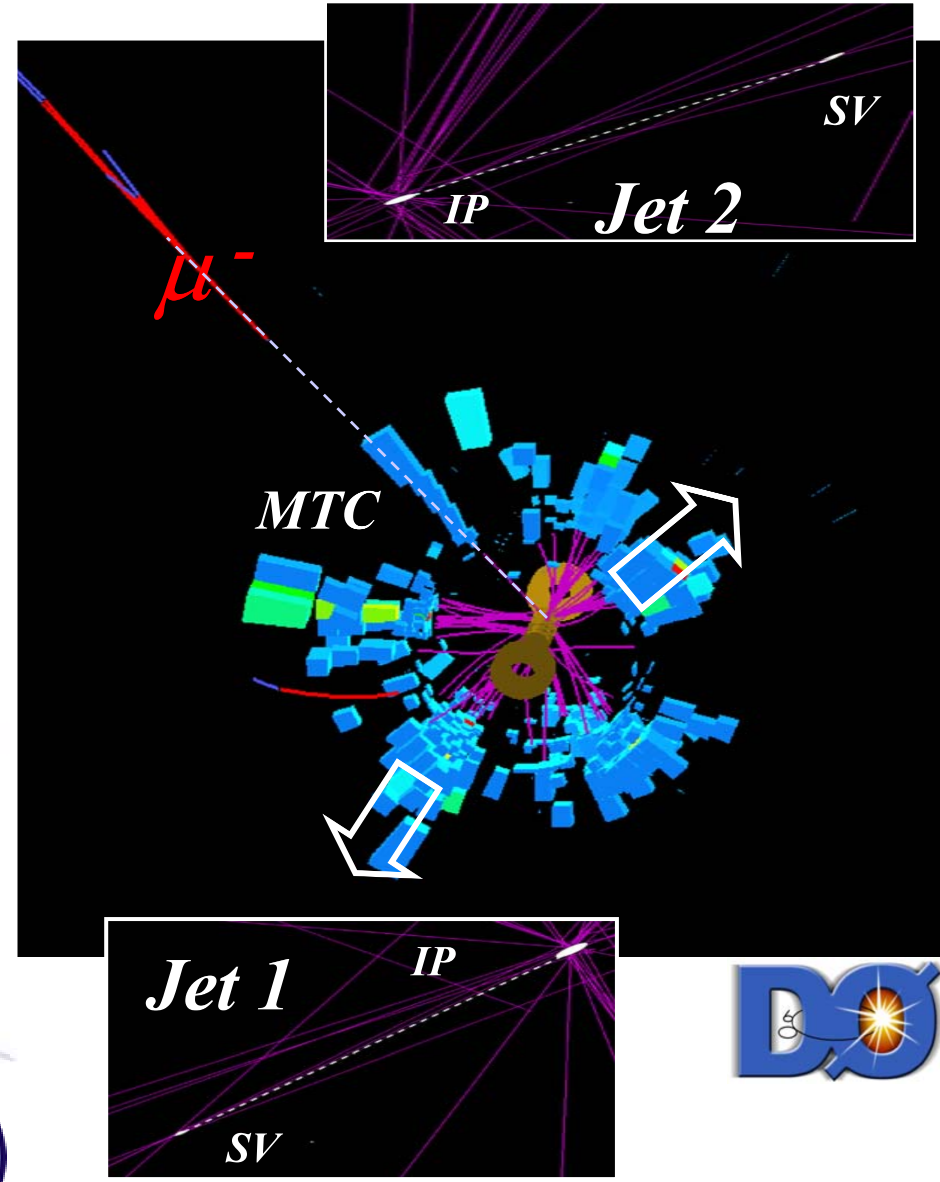
The Run II Top Physics Program has begun



μ_1
μ_2
Jet$_1$
Jet$_2$
Et = 26.65 GeV
3 meters
Tracking view

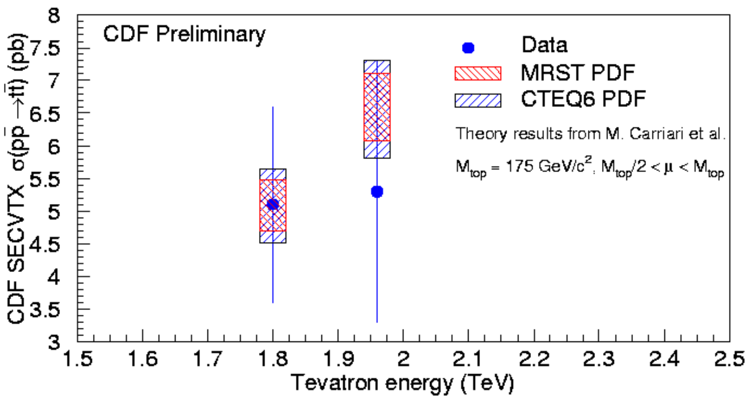


μ_1
μ_2
Primary vertex
Secondary vertex
Jet$_2$
Jet$_1$
Vertex view



SV
IP
Jet 2
μ^-
MTC
Jet 1
IP
SV

The top quark rediscovered, 2003

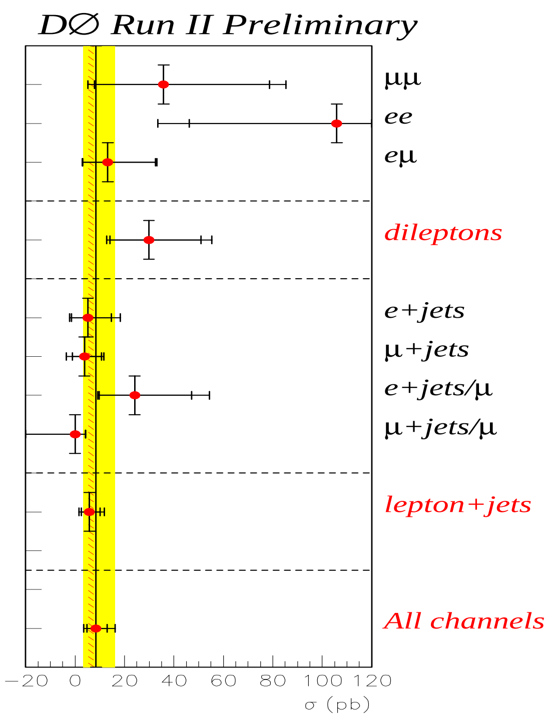


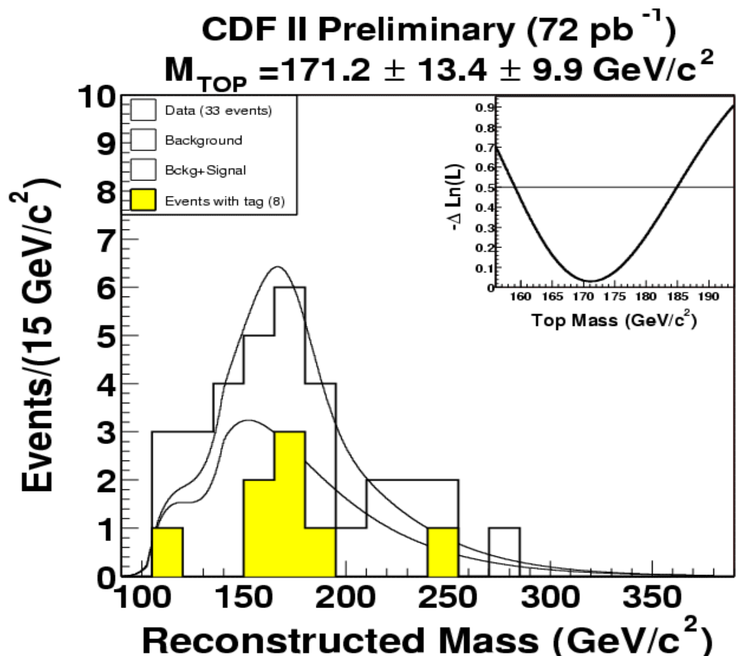
Cross section

CDF dileptons $\sigma = 13.2 \pm 5.9_{stat} \pm 1.5_{sys}$ *pb*

CDF l + jets $\sigma = 5.3 \pm 1.9_{stat} \pm 0.8_{sys} \pm 0.8_{lum}$ *pb*

DØ (comb.) $\sigma = 8.5\ ^{+4.5}_{-3.6}\ (stat)\ ^{+6.3}_{-3.5}\ (sys) \pm 0.8 (lum)$ *pb*





CDF mass

$M_{top} = 171.2^{+14.4}_{-12.5\ stat} \pm 9.9_{sys}\ GeV/c^2$

Q:

- **What is the dark matter that seems to be responsible for structure in the universe?**
  - **Is it a new kind of particle?**
  - **Does this point to a previously undiscovered symmetry of the universe?**

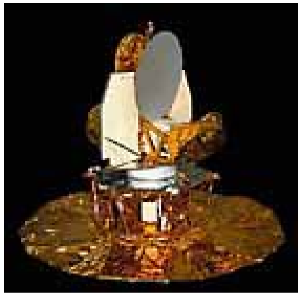
Mass shapes the Universe

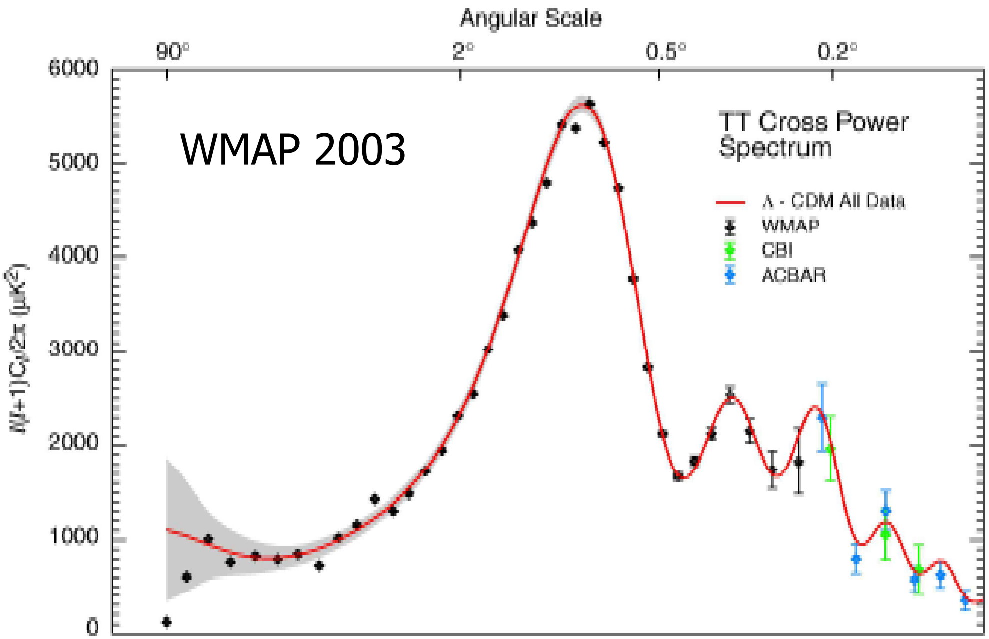
…through gravitation, the only force that is important over astronomical distances

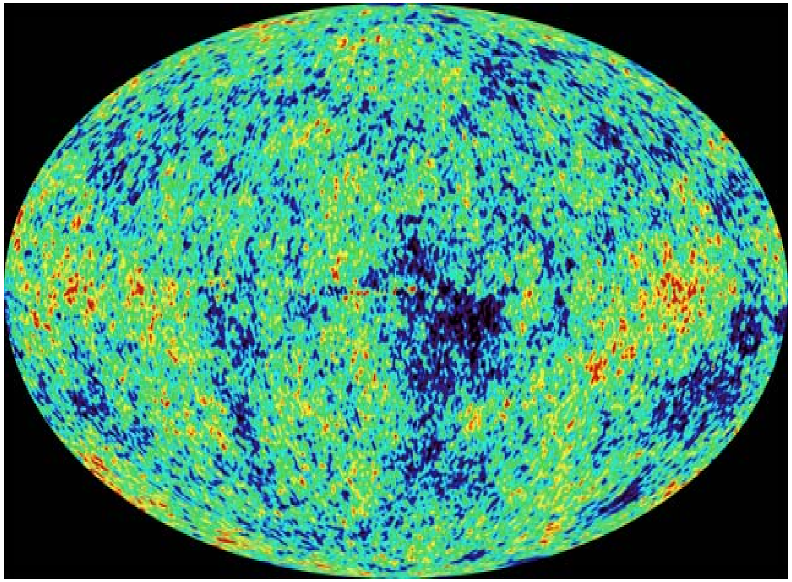
- **Masses of Atoms**
  - binding energies from the strong force (QCD)
- **Dark Matter**
  - Long known that dynamical mass much greater than visible luminous material
  - Primordial nucleosynthesis, D/He abundance measures baryon density

Cosmic Microwave Background

- Recent measurements of “acoustic peaks” vs. multipole number







What is Dark Matter?

Compare with cosmological models

- Size of DM “potential wells” into which matter fell
- Allows matter and DM densities to be extracted

→ About six to seven times more mass (27±4%) than there is baryonic matter (4.4±0.4%)

- new particles?
  - Weakly interacting, massive relics from the very early universe

- Two experimental approaches:
  - Search for dark matter particles impinging on earth
  - Try to create such particles in our accelerators

Supersymmetry

- Postulate a symmetry between bosons and fermions:
  - all the presently observed particles have new, more massive superpartners (SUSY is a broken symmetry)
- Theoretically nice:
  - additional particles cancel divergences in the Higgs mass
    - solves a deficiency of the SM
  - closely approximates the standard model at low energies
  - allows unification of forces at much higher energies
  - provides a path to the incorporation of gravity and string theory: Local Supersymmetry = Supergravity
- Predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos
  - masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV

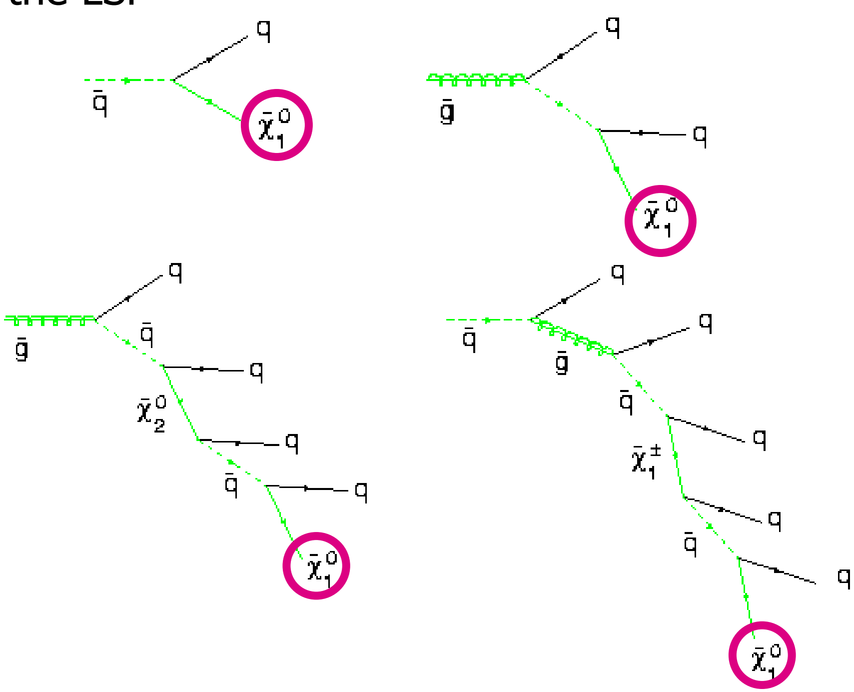
Lightest neutralino is a good explanation for cosmic dark matter
Potentially discoverable at the Tevatron

Supersymmetry signatures

- **Squarks and gluinos are the most copiously produced SUSY particles**
- **As long as R-parity is conserved, cannot decay to normal particles**
  - **missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)**

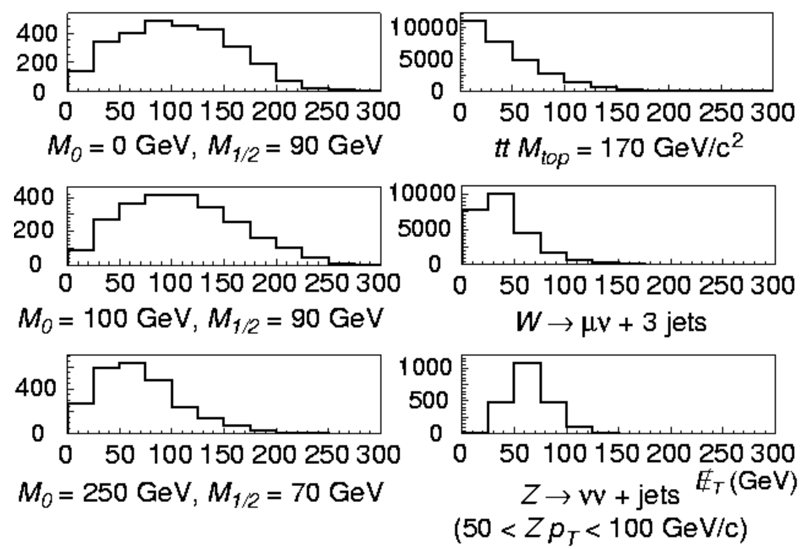
Make dark matter at the Tevatron! → **Detect its escape from the detector**

Possible decay chains always end in the LSP



Missing E_T

SUSY **backgrounds**



Search region typically > 75 GeV

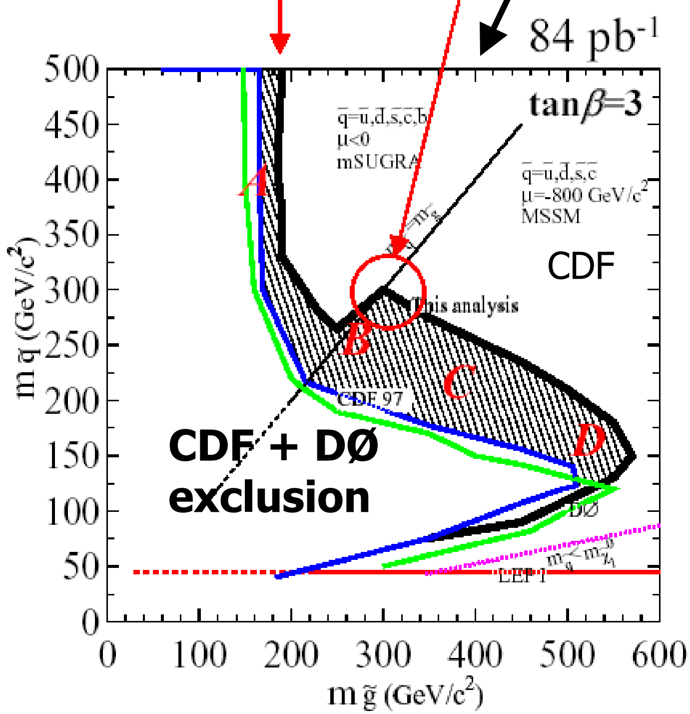
Searching for squarks and gluinos

Run I

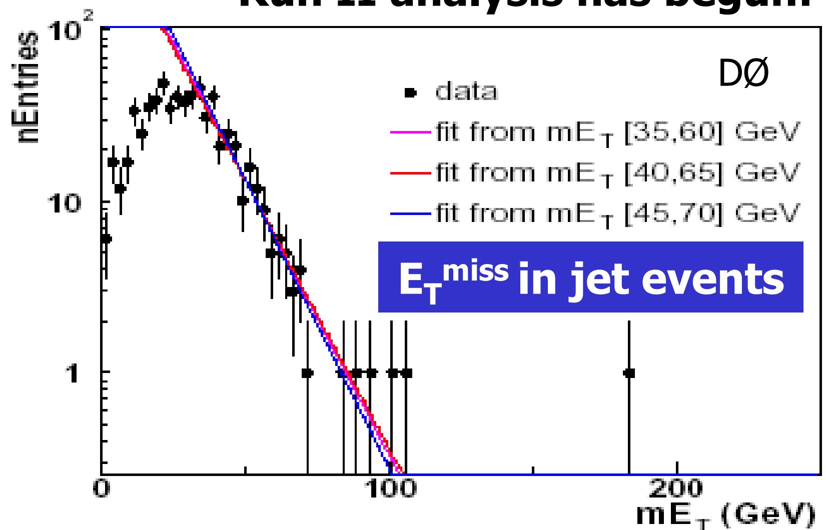
$M_{\tilde{g}} > 300$ GeV/c^2 $M_{\tilde{q}} \approx M_{\tilde{g}}$

$M_{\tilde{g}} > 195$ GeV/c^2

With 2 fb^{-1}:
Reach in gluino mass ~ 400 GeV



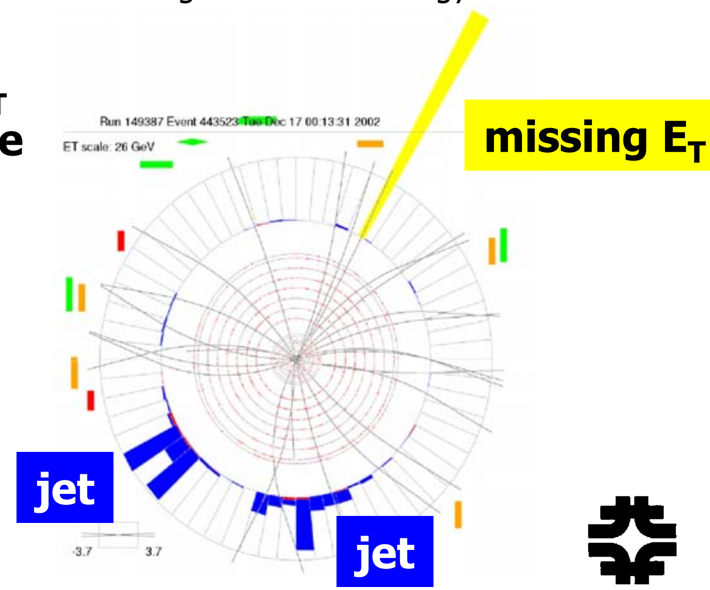
Run II analysis has begun:



Missing Transverse Energy

High ME$_T$ candidate event

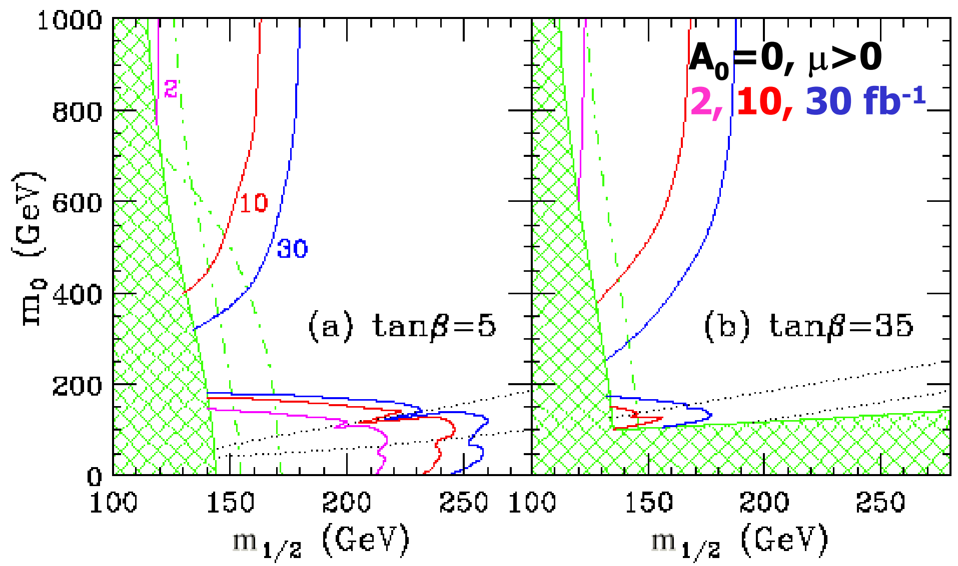
DØ

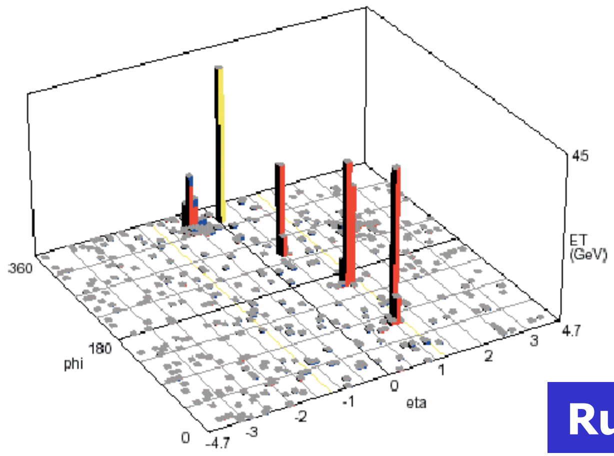


John Womersley

Chargino/neutralino production

- "Golden" signature
  - Three leptons
    - very low standard model backgrounds
- This channel becomes increasingly important as squark/gluino production reaches its kinematic limits (masses ~ 400-500 GeV)
- Reach on $\chi^{\pm}$ mass ~ 180 GeV (tan β = 2, μ< 0)
  ~ 150 GeV (large tan β)





Searches have begun!
So far number of events is consistent with expectations — we need a lot more data, but the tools are in place

Run II Trilepton candidate

Q:

- **What is the structure of spacetime?**
  - **How many dimensions are there?**
  - **Is geometry the way to connect gravity to the other forces?**

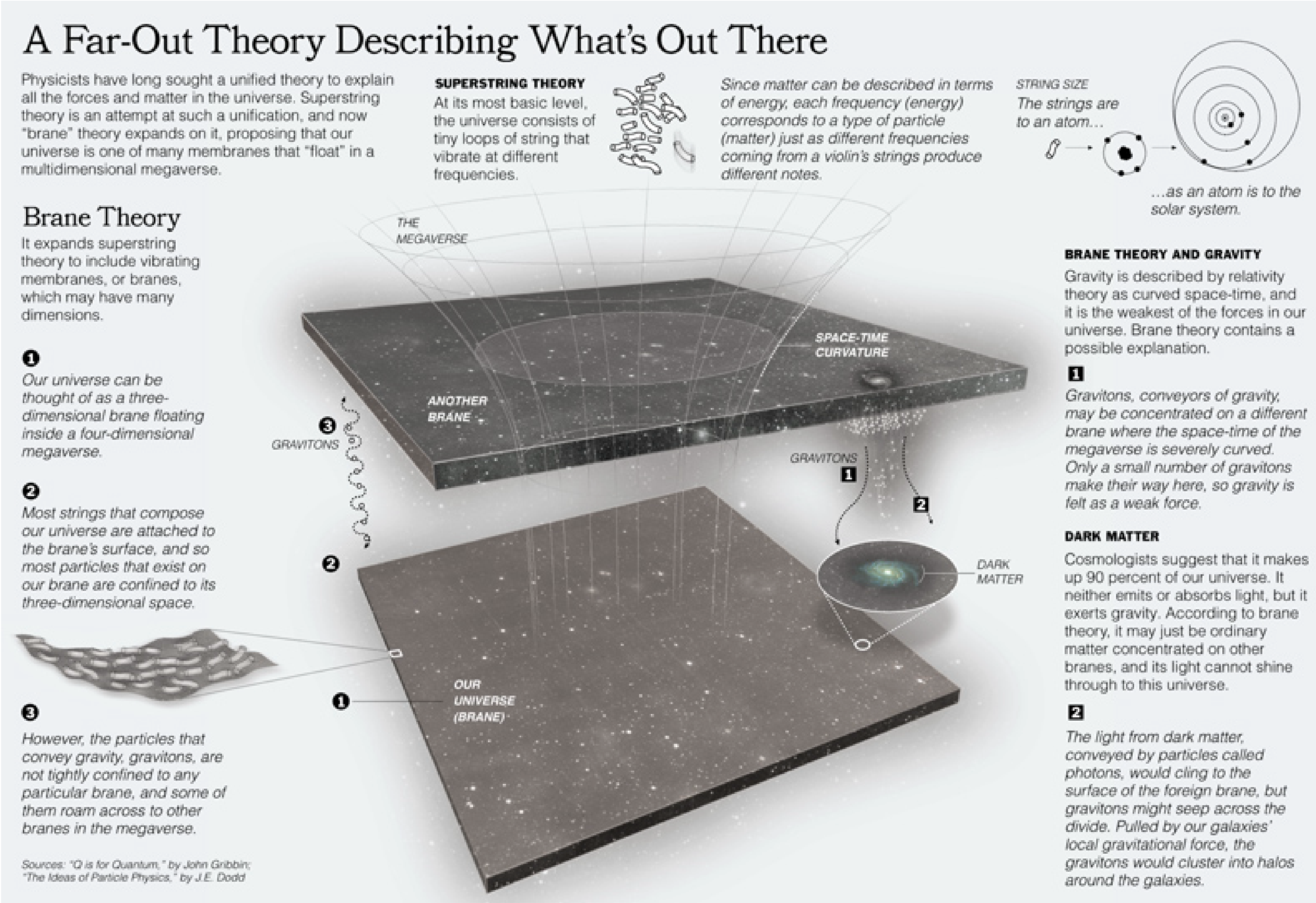
Connections with Gravity

- While supersymmetry is required for supergravity, it was usually assumed that any unification of forces would occur at the Planck scale ~ 10^{19} GeV
  - very large hierarchy between the electroweak scale and gravitational scales

- Powerful new idea:
  Gravity may propagate in extra dimensions, while the gauge particles and fermions (i.e. us) remain trapped in 3+1 dimensional spacetime
  - extra dimensions not necessarily small in size (millimeters!)
  - true Planck scale may be as low as the electroweak scale
  - Gravity could start to play a role in experiments at ~ TeV

- Many different theoretical ideas, with different topologies possible
  - large extra dimensions (ADD)
  - TeV scale extra dimensions
  - warped extra dimension (RS)

New York Times

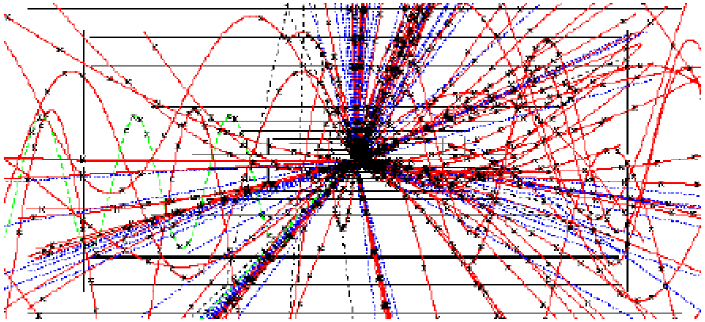


Steve Duenes/The New York Times

John Womersley

TeV-scale gravity

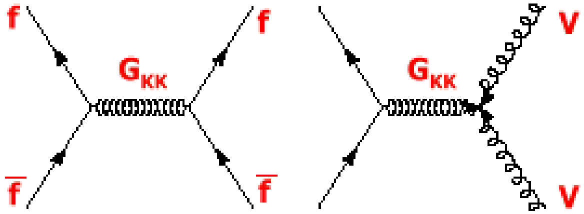
- **Observable effects can be direct and spectacular . . .**



Production of Black Holes may even occur

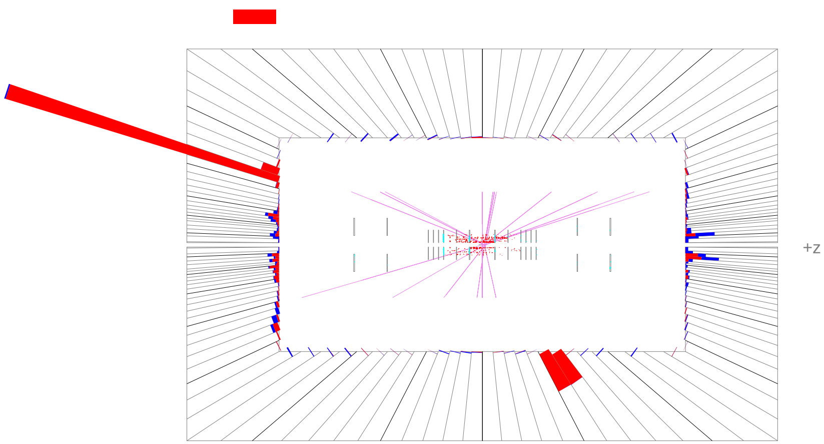
Decay extremely rapidly (Hawking radiation) with spectacular signatures

- **Or indirect . . .**
  - **Virtual graviton exchange can enhance the production rate for e^+e^- and $\gamma\gamma$ pairs with large masses and angle relative to the beamline**



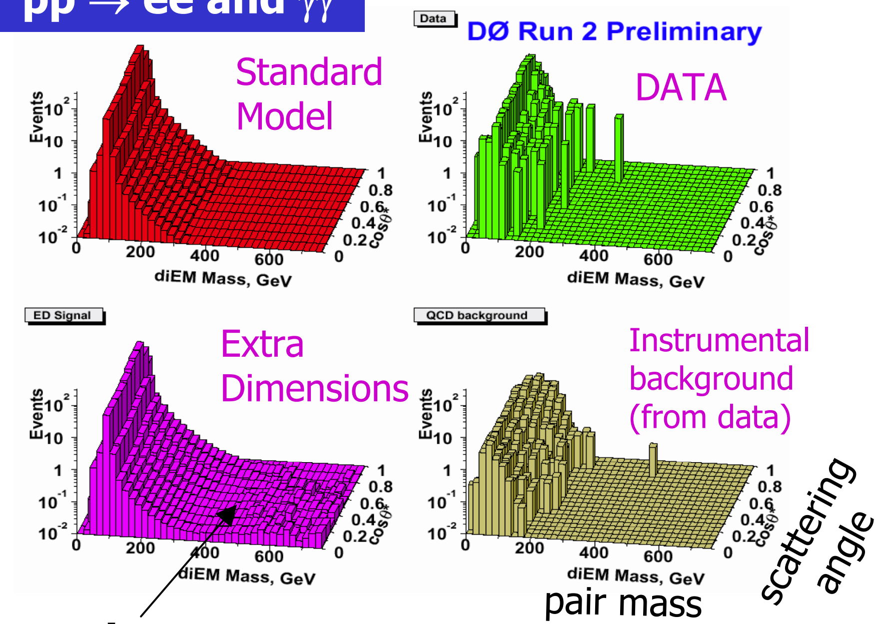
Searching for Extra Dimensions

- **We have started this analysis with Run II data**



High-mass electron pair event

$\bar{p}p \rightarrow$ ee and $\gamma\gamma$



Signal is an excess of events at large mass and large angle

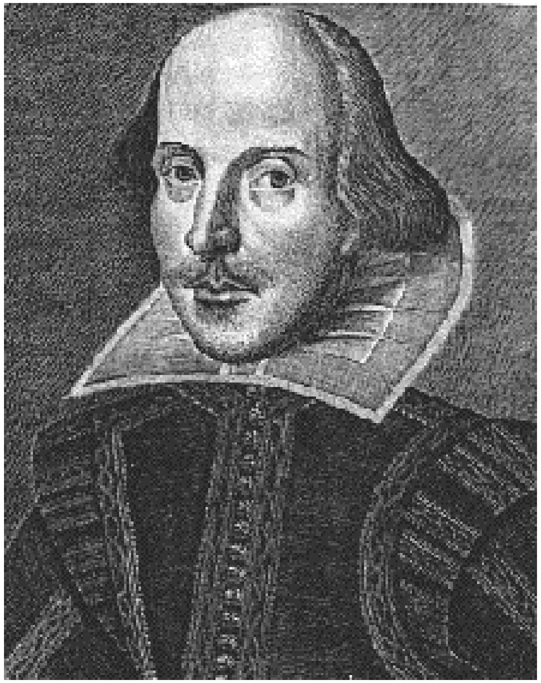
First Run II limits from $\bar{p}p \rightarrow ee, \mu\mu, \gamma\gamma$ (summer 2002)

M_S(GRW) > 0.92 TeV (ee/$\gamma\gamma$)

M_S(GRW) > 0.50 TeV ($\mu\mu$)

Are we asking the right questions?

There are more things in heaven
and earth, Horatio,
Than are dreamt of in your
philosophy. — *W.S.*



- **We need a way to search for new phenomena that is not constrained by our preconceptions of what might be "out there."**

Sleuth

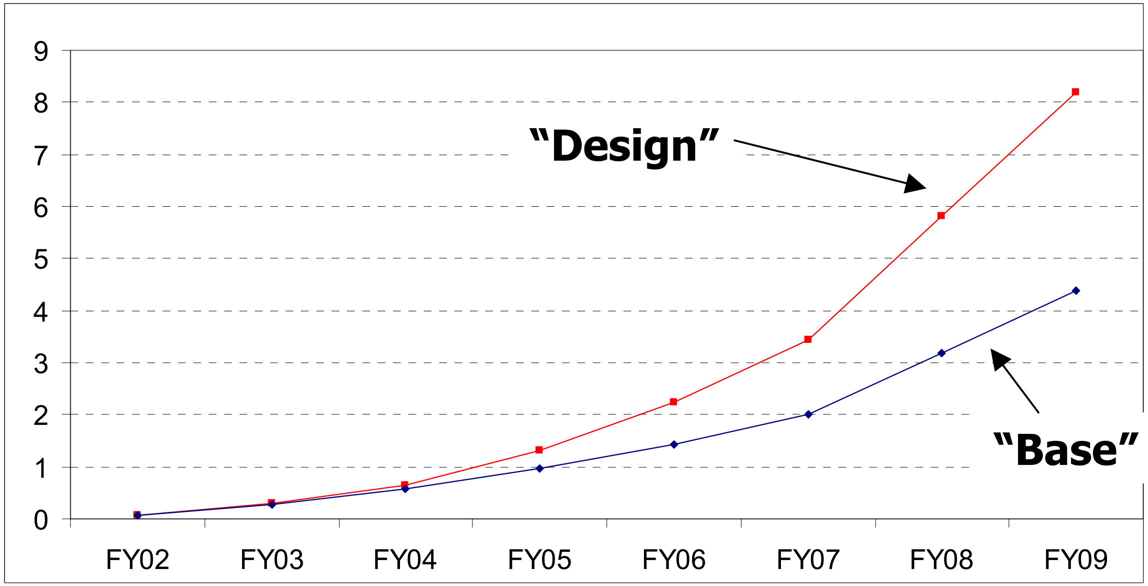
- A new approach from DØ: attempt at a model-independent analysis framework to search for new physics
  - will never be as sensitive to a particular model as a targeted search, but open to anything
  - searches for deviations from standard model predictions
- Systematic study of 32 final states involving electrons, muons, photons, W's, Z's, jets and missing E_T in the DØ 1992-95 data
- Only two channels with some hint of disagreement
  - 2 electrons + 4 jets
    - observe 3, expect 0.6± 0.2, CL = 0.04
  - 2 electrons + 4 jets + Missing E_T
    - observe 1, expect 0.06±0.03, CL = 0.06
- While interesting, these events are not an indication of new physics, given the large number of channels searched
  - 89% probability of agreement with the Standard Model (alas!)

This approach will be extremely powerful in future!

Short term prospects

- **For the spring conferences, we "rediscovered" the top quark, and presented results with ~ 50pb^{-1}**
- **For this summer's international conferences, and for papers this fall, we will present physics results from Run II with ~ 100-150 pb^{-1}**
  - **increased sample over Run I with improved detectors and a higher center of mass energy**
    - **Top quark measurements with increased statistics and purity**
      - Cross section is 35% higher
      - Silicon b-tagging capability
    - **Increased statistics W and Z samples, multiboson samples**
    - **Start to explore the B sector**
    - **Jet cross section at high E_T**
      - constrain the gluon PDF
    - **New limits on physics beyond the Standard Model**
      - e.g. MSSM A/H at large tan β
    - **. . .**

The longer term future



- To realize the full potential of Run II we must continue to upgrade and invest in the detectors and the accelerator
- We will run CDF and DØ until the LHC experiments start to produce competitive physics results
  - should be prepared to run until the end of the decade

Conclusions

- The Tevatron Collider at Fermilab is the world's highest energy accelerator
- In studying high energy collisions between the fundamental constituents of matter, we are not just trying to understand these constituents, we are trying to address big questions about the universe

  For example
  - What is the cosmic dark matter?
  - Is the universe filled with energy?
  - What is the structure of spacetime?
- This physics program is based on the detailed understanding of Standard Model particles and forces that we have obtained over the last few decades
  - we are guided by theory but also open to the unexpected
- It's fun!